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# 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 sea 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. Namely, by virtue of the utilization magnetrons in ovens, millions people over whole world have learned the word “microwave”!

However by the middle of 60<sup>th</sup> 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 60<sup>th</sup> 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  $\pm 1\%$  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 80<sup>th</sup>. 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  $\pi$  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 autoemitters	Cold with auxiliary thermionic cathode	Metallic alloy (?)
Frequency agility	Yes	No	No	No
Life time, hours				No information
Producer specified	>2000	>2000	>1000	
Reached during utilization	>10000 >30000		>5000 >10000	
Average				
Maximal				
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<sup>th</sup> (Usikov, 1972). Ab initio they utilize operation at spatial harmonics different from  $\pi$  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<sup>th</sup> (Naumenko et al, 1999). It characterized by a guaranteed life time of 2000 hours. By the end of 90<sup>th</sup> 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 recent time a low voltage, compact Ka band magnetrons with cold secondary emission cathode are under

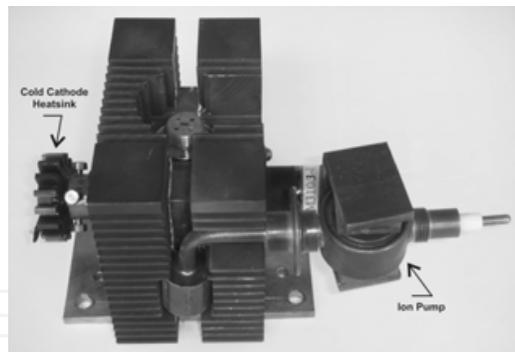


Fig. 1. 4 kW, W band magnetron with cold secondary emission cathode and extended life time.

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) <sup>1</sup> 4 (4) <sup>1</sup>	1 (300) <sup>1</sup> [50 (500)] <sup>2</sup> 1 (10) <sup>1</sup> [3 (300)] <sup>2</sup>	3 (300) <sup>1</sup> 1.5 (90) <sup>1</sup> [1.5 (150)] <sup>2</sup>	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.

<sup>1</sup> Air or conductive cooling

<sup>2</sup> 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<sup>th</sup> 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 al, 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 recent 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:

$$P_{incoh}/P_{coh} = NFl \cdot PRF, \quad (1)$$

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  $i^{\text{th}}$  pulse from a constant value of  $\lambda_0$ . 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:

$$S_i = A \cdot \left( (\sin \varphi_0 + i \cdot \cos \varphi_0) + \varphi_0 \cdot \Delta\lambda_i/\lambda_0 \cdot (\sin \varphi_0 - i \cdot \cos \varphi_0) \right), \quad (2)$$

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	1
Rx path	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	180
at -1 dB	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	9U
Receiver	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,  $\lambda$  of 8.2 mm, and R of 5.5 km results in pulse-to-pulse frequency instability of about .

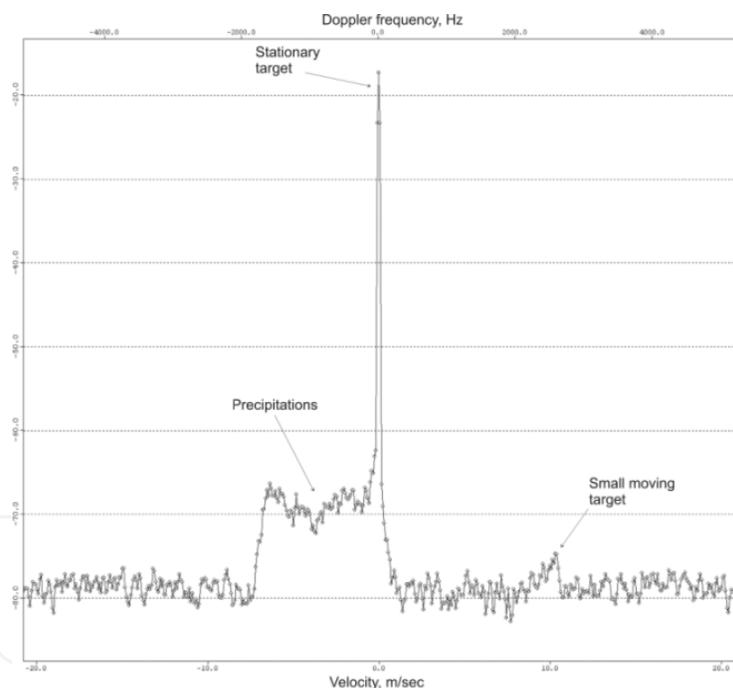


Fig. 3. Doppler spectrum from stationary target located at 5.5 km distance retrieved with Ka band meteorological radar.

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

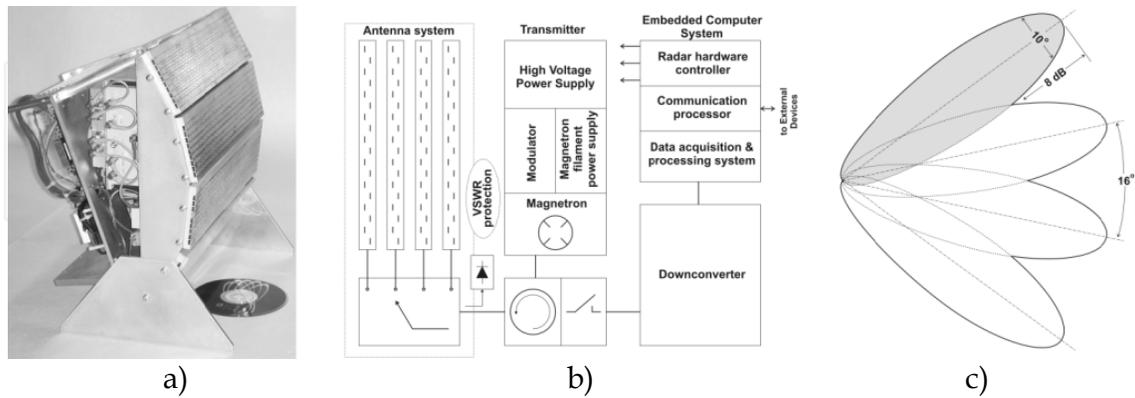


Fig. 4. Outline (a), block diagram (b), and antenna pattern (c) of Ka band airborne scanning radar.

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	1.5
Rx path	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 <sup>2</sup>	-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.

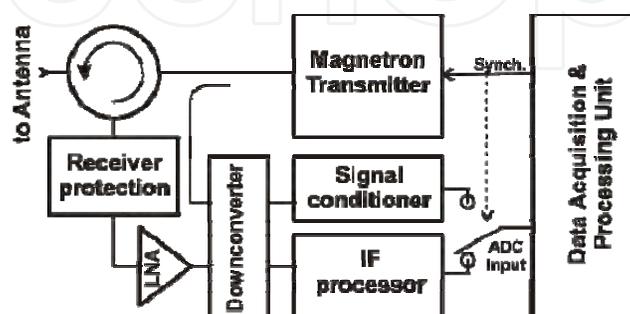


Fig. 5. Typical block-diagram of magnetron based radar.

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:

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

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

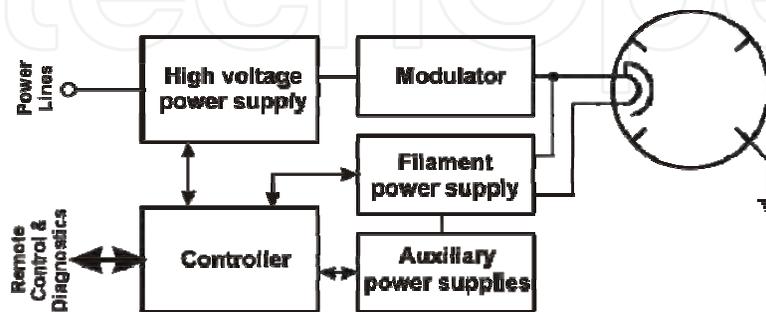


Fig. 6. Block-diagram of magnetron transmitter.

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 from 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.

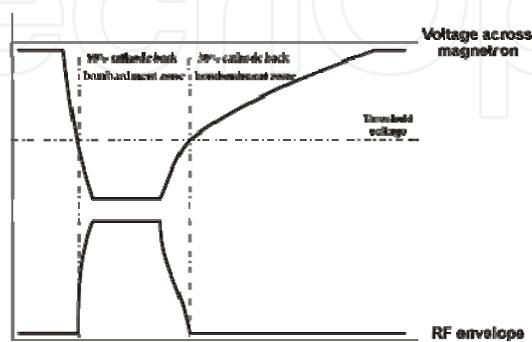


Fig. 7. Waveforms of voltage pulse across magnetron and RF envelope.

Now, when the essential requirements to the modulator circuits have been outlined, some design approaches to meet them can be discussed. Either modulator contains the following parts: (i) energy storage; (ii) a switch or switches, which provides applying voltage across the magnetron within definite time intervals only; (iii) circuits to match the modulator output and the magnetron; and (vi) protection and decoupling circuits. From a variety of modulator types being in use, a line modulator and a modulator with partial discharge are utilized practically exclusively in magnetron transmitters (Sivan, 1994).

A simplified block-diagram of a line modulator is depicted schematically in Fig. 8. A delay line arranged as a piece of cable or assembled from lump inductors and capacitors is used as both to store energy and to form the trailing edge of the pulse across magnetron.

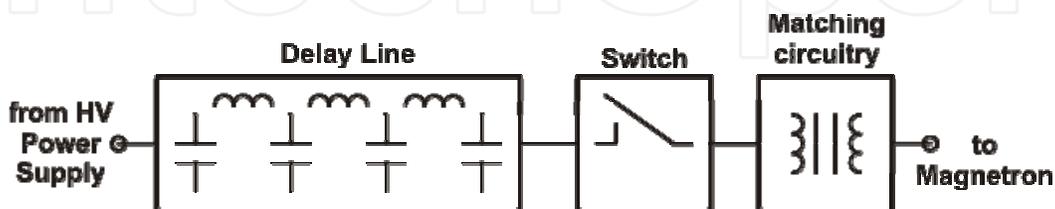


Fig. 8. Block diagram of line modulator.

The utilization of line modulators provides the following advantages: (i) not only fully controlled devices like a hard tubes or MOSFETs may be used in the high voltage switch but also thyristors or thyratrons, which are rated fundamentally to work at much higher currents and voltages (MOSFET *vs.* thyristors comparison); demonstrate a greater efficiency in general; and do not require a precise shape of triggering pulse; (ii) the mandatory utilization of the step-up transformer to match the impedances of delay line and magnetron; (iii) practically complete cancellation of the possible magnetron damage in the case of breakdown due to the total energy stored in the delay line is limited. All above result in the overall complexity and total cost of a transmitter equipped with the line modulator are probably the lowest as compared with other types.

However there are a number of serious disadvantages of such type of modulator. The first is the usage of a lumped element delay line leads us to oscillations appear at flat part of the pulse. Next, it is practically impossible to implement smooth regulating of the output pulse duration. Further, the inherent utilization of the transformer results in the introduction of significant distortions of the modulator output pulse especially due to there is a strong nonlinearity of magnetron volt-ampere characteristic as well as possible appearance of its sensitivity from the voltage rate across the magnetron (Okress, 1961). It makes difficult matching the impedances of the delay line and the magnetron during the leading and trailing edge of the modulation pulse. Both numerical simulation and the experience of utilizing modulators equipped with a transformer prevent us to recommend such approach to be used in the high performance radars. On other hands it should be accepted that almost all mentioned disadvantages of the line modulators are important to achieve the maximum radar performance only and cause no problems in a variety of simple and low cost magnetron based systems.

Another type of high voltage modulator used to drive magnetrons is so called modulator with partial discharge (Sivan, 1994). The essential difference of such type of the modulator from the line modulator is only a small part of energy accumulated in an appropriate

storage is used to form the output pulse. A capacitor is used as the energy storage in the magnetron modulators exclusively. Due to such type of the modulator does not require the utilization of matching circuitry conceptually it provides a much better shape of the output pulse than the line modulator.

A variety of variants can be used to build the modulator with partial discharge. Some of basic configurations are depicted in Fig. 9. Let us consider briefly advantages and disadvantages provided by each of them. The first scheme is traditionally used more frequently than other configurations. It is due to the high voltage switch is grounded, which is a great advantage for whichever hard tube based modulator. In this case a filament and bias power supplies for the modulator tube are grounded also, simplifying considerably the modulator design. This issue is not so important for a solid state switch, arranged usually as a stack of transistors connected in series. Actually, a galvanic decoupling is required anyway to drive each transistor independently on either the high voltage switch is grounded or not.

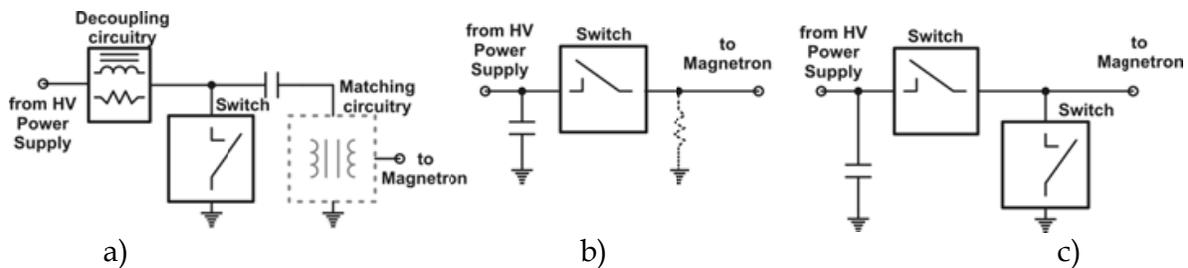


Fig. 9. Schemes of the modulator with partial discharge.

A resistor or choke may be used to decouple the switch from the output of high voltage power supply during interval of pulse formation. In the case of resistor utilization, the distortions of magnetron pulse during its front and flat part are minimal due to no component with frequency dependant impedance is in the pulse formation network. In order to decrease duration of the trailing edge of the output pulse the resistance of the resistor should be chosen small enough, which results in lower modulator efficiency. If a choke is used instead the resistor, the efficiency is better fundamentally. In addition there is a possibility to produce the output pulse with amplitude, which is higher than the value of modulator supply voltage. However due to the pulse formation network includes a reactive component, the output pulse distortions are higher in the case of the choke utilization. Next, generally, there are big constructive difficulties to design a charging choke with required parameters taking into account it is under high pulsed voltage condition. As usual such component is bulky and characterized by a rather large weight as compared with other parts of the modulator. Thus we would not like to recommend the utilization of modulator with inductive decoupling in modern high performance magnetron based radars. Probably only if retrieving of very short pulses at a high repetition rate is required (see (Belikov et al, 2002)), such scheme may appear to be the most optimal choice.

A simplified block-diagram of the modulator with a floating high voltage switch is depicted in Fig 9.b The only capacitor may be used both as the output capacitor of the high voltage power supply and storage capacitor of the modulator. No decoupling circuits are required conceptually in this case. Nevertheless, as mentioned above if a high PRF is suggested, an additional resistor to decrease the duration of the output pulse trailing edge is required as depicted in Fig. 9.b by a dash line. It is difficult evidently to use a hard tube in such circuit

configuration. Instead, from our opinion, it is the most preferable scheme to utilize a solid state high voltage switch.

The push-pull scheme of the modulator is depicted in Fig. 9, c. It provides the tightest control of the output pulse shape as well as the highest energy efficiency among the schemes discussed before. The expense for that is much more complexity in design as compared to previous solutions. It is one of the reasons why the modulators utilizing such approach may be found in a very limited number of radars despite its evident advantages.

Let us now discuss some issues concerned to the selection of an appropriate electronic device to build the high voltage switch. According to modern tendencies solid state devices should be considered as first choice while designing any new electronic system. Two types of solid state devices, namely, MOSFETS, and IGBT may be used in magnetron modulators. Despite IGBT are superior generally to MOSFETs as respect to both maximal rated voltage and current, as well as efficiency provided, they are characterized by a lower switching speed and an attitude to a second-induced breakdown, which confines the overall reliability of the modulator. Thus, MOSFETs remain the only choice among solid state devices to use in the magnetron modulators intended for high performance millimeter wavelength radars featured by rather short operational pulse width.

Hard tubes were historically the first devices used to build high voltage modulators in radars. They remain to be utilized widely until now despite a serious competition from solid state devices. A considerably greater robustness should be indicated as an essential reason. High voltage circuitry have a strong attitude to appearance of various local breakdowns, leakages etc, which are difficult to control and prevent especially for long-term unattended radar operation. Such phenomena stress the modulator parts greatly. Energy to destroy a hard tube is on orders higher than that for any solid state device. Next, the only tube can be used practically always to build any modulator. Instead the limitations for currently available powerful MOSFETs in the maximal rated voltage, makes inevitable utilizing a stack arranged from many transistors connected in series and, possibly, parallel in order to achieve the modulator parameter being enough to drive the most magnetrons. Utilization of pulse transformer allows in principle to minimize number of the transistors used but, as mentioned above, causes considerable pulse distortions. Certainly there is a well-known disadvantage of hard tubes, namely, a limited life time. We dare to claim that it may be considered as almost virtual at the time being. The situation is very similar to that mentioned above for the magnetrons. A current state of cathode manufacturing as well general state of vacuum technique makes expected lifetime of the modulator hard tubes of several ten thousand hours very realistic. These expectations were ascertained completely by our experience of utilization of hard tube based modulators in the line of meteorological radars (see Section 3). The above consideration allows us to make a conclusion that despite of a strong competition from solid state devices, partially MOSFETs, hard tubes are keeping their positions under development of modern magnetron based radars. The only issue may prevent using them in the modulators, namely, their commercial availability and assortment, which decreases actually generally at the time being due to, essentially, a shortage in demand from non-radar application. Certainly we do not mean a fantastic breakthrough in the development of high voltage, high power semiconductor devices, which makes all hard tubes obsolete at one bout!

It should be noticed that the modulator may operates as either voltage or current source. The latter is conceptually better for any cross-field vacuum tube (Sivan, 1994). On other

hand the introduction of the current mode in the modulator makes its design more complex especially in the case if a short pulse length is required. Our experience demonstrates that providing an appropriate stability of the high voltage power supply it is possible to achieve a great magnetron performance even if the much simpler voltage mode is utilized in the modulator. Nevertheless, the development of a modulator, operating in the current mode, remains the greatest challenge a designer faces from our opinion.

#### **4.2.4 Magnetron filament and protection circuits**

As mentioned in Section 0, keeping an adequate condition of the cathode surface is the most important issue to prolong the magnetron lifetime. It depends on the following factors: (i) cathode temperature; (ii) vacuum condition inside the magnetron; (iii) electron back bombardment.

The cathode temperature depends both of a filament power applied and the power dissipated on the cathode due to its back bombardment. This temperature should be kept within a rather narrow interval of several tens degrees typically. Thus, the filament power supply should ensure a very tight control of the magnetron filament power as well as provide a dedicated procedure to regulate it depending on the parameters of the magnetron operational mode. In the developed radars (see Section 0) the following proven principle is used. The filament power supply comprises of two parts, low and high side ones correspondingly. The low side part is simply PWM inverter equipped with either analog or digital controller. The high side includes a high voltage decoupling transformer, a rectifier, and a dedicated controller. It should be noticed that we consider that DC filament voltage should be used to supply magnetron filament due to in this case a possible alternating of the magnetron frequency is canceled. The controller is used to measure both filament voltage and current and to transfer the corresponding data to the low side in a digital form. An optical link is used for such communication. The above approach provides accurate and independent measurement and control of the magnetron filament parameters.

The vacuum conditions inside the magnetrons depend not only on quality of manufacturing routine and materials it is made of. Electrical breakdowns affect them strongly. In general, it is considered that the magnetrons demonstrate a rather strong attitude to the development of breakdowns. They may cause in addition direct magnetron damage if no current limiting is provided by the modulator circuitry. It is important for the millimeter wavelengths magnetrons especially due to such magnetrons are characterized by a rather delicate structure of cavities. Hard tubes provide inherently such current limitation, which can be regulated moreover. MOSFETs are featured similarly, but it is difficult to regulate a limit value due to the high voltage switch consists always of several devices connected in series. As a result, this limit is defined by the maximal rated current of the transistors used. Certainly, there is a contradiction between the necessity both to limit the output current and to ensure a minimal settling time of the output voltage of the modulator.

Our experience demonstrates that there is a simple way to prevent possible worsening of the magnetron parameters due to breakdowns without a noticeable degradation in the shape of its output pulse. Namely ferrite beads should be connected in series with the magnetron. This effect may be explained as follows. Breakdown in the magnetron appears usually in two stages. The first stage caused by field emission from a tip located somewhere inside magnetron. This stage runs very fast, typically during several nanoseconds. It cause negligible damages of the magnetron internal parts, but initiates developing the next stage

brought by a local overheating, copper sputtering, and further arcing. This stage requires much longer time to run but can cause significant degradation of the magnetron performance.

The ferrite beads demonstrate rather high impedance under transient conditions. Thus, it leads to fast decrease in the voltage across magnetron during the first stage of the breakdown and prevents developing of the second stage. Moreover the magnetron keeps producing RF oscillations as usual. There are some more benefits from the utilization of ferrite beads. They restrict the change rate of magnetron current resulting in a great reduction of electromagnetic interferences and an increase to overall stability of the transmitter operation. In addition such beads may improve the output pulse shape weakening the influence of stray circuit inductance and capacitance on the pulse front formation. It should be noticed that the usage of ferrite beads is practically mandatory if MOSFET based high voltage switch is used in the modulator. Such devices are characterized by rather low rated  $dU/dt$  capability. According to a numerical simulation and experimental investigations, an excess in this value is an essential reason of transistors damage during transients in the magnetron.

At last, it should be noticed that there are evidences that influence of the cathode back bombardment is not limited by thermal effects only as mentioned above. Change in the cathode surface condition has been fixed even after single pulses. Probably it is due to a very high value of instantaneous power of the back bombardment, which is about 10 % of anode power at a nominal anode voltages and much more – up to 30 % - at lower voltages. In order to minimize effect of back bombardment it is necessity to keep the duration of the modulation pulse trailing edge as shorter as possible (see Section 0)

## 4.3 Receiver

### 4.3.1 General consideration

The principles to develop receivers for the magnetron based radars are the same as for any other systems. Nevertheless, we would like to discuss below some design approaches, which have proven their efficiency in a number of radars developed in the Institute of Radio Astronomy of National Academy of Sciences of Ukraine.

A simplified block-diagram of a full-featured double channel receiver used in the most modern modifications of Ka band magnetron based meteorological radars (see Section 0) is depicted in Fig. 12. It may be considered as typical and reflecting the essential design approaches. At first, double frequency conversion is used in the receiver. It makes the receiver design more complex apparently, but simplifies greatly the design of local oscillators as well as allows utilizing a simple filtration to reject image frequency. The local oscillator(s) should meet the following requirements: (i) cover wide enough frequency range – typical values of possible frequency variation are 500 MHz for Ka band and 700...1000 MHz for W and G band magnetrons respectively; (ii) provide frequency tuning with a relatively small step; and (iii) ensure a low phase noise with a fast roll-off beyond the band of  $\{-PRF/2; PRF/2\}$ , which corresponds to the unambiguous frequency range of Doppler processing.

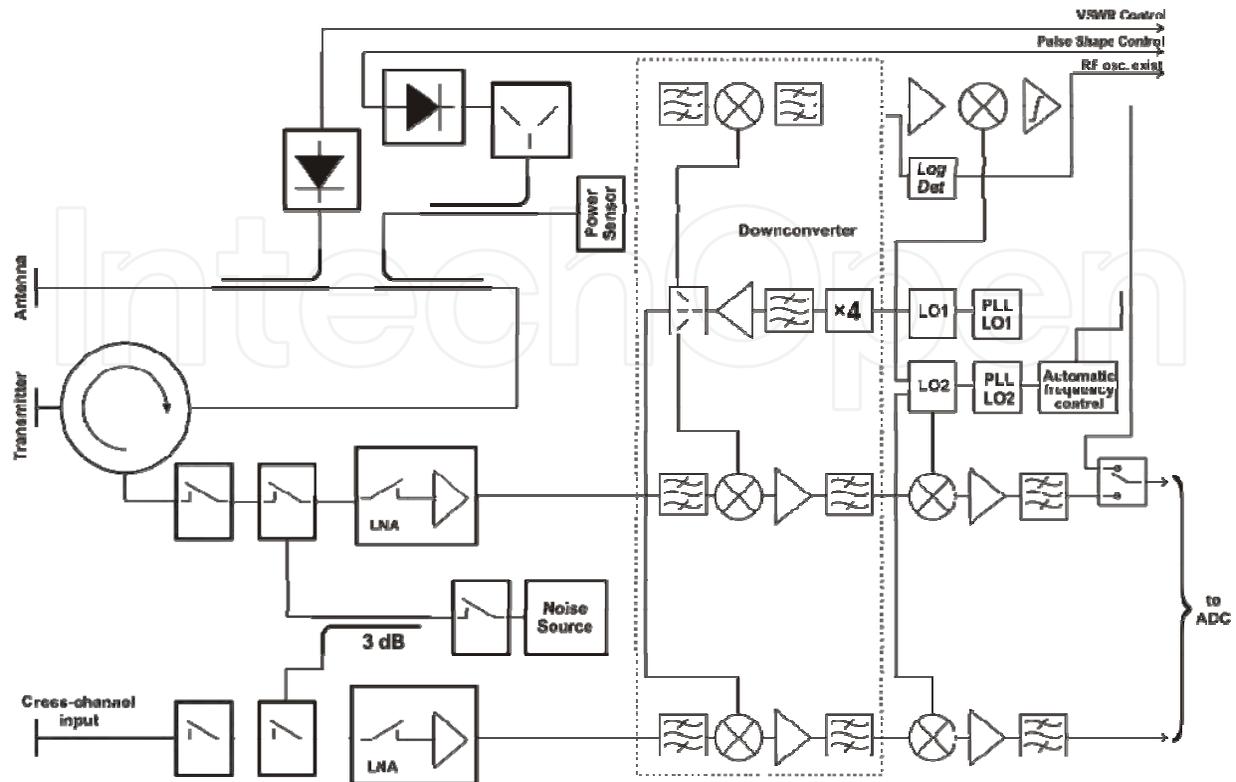


Fig. 10. Block-diagram of receiver for magnetron based Doppler radar.

The latter is required to avoid an increase in the noise floor of coherence-on-receiver processing. In the case of double frequency conversion the first local oscillator operates at a fixed frequency, which makes its design relatively simple. As usual a dielectrically stabilized oscillator with frequency multiplier provides enough performance level for the most cases. If quality of Doppler processing provided by a radar is not an issue, the utilization of single frequency conversion simplifies its design significantly (Volkov et al, 2007)

Next point we would like to discuss is a methods to couple a sample of the transmitted RF pulse to the data acquisition unit to implement coherence-on-receiver processing. An evident way is to use a separate downconverting channel as depicted in Fig. 10. This way provides the highest possible performance but requires additional hardware to be used. Instead a signal, leaked through the receiver protection circuitry, may be used in the way illustrated by Fig. 11. In this case newly introduced circuits operate at the intermediate frequency only. This way is certainly much simpler but characterized by the following disadvantages: (i) an additional phase jitter may be introduced by an antenna environment; (ii) as usual the receiver circuitry operates in a deep saturation, which may cause additional phase instability. Several radars have been developed by utilizing the above approach to pick a sample of the transmitted pulse up. They demonstrated a solid Doppler performance. Nevertheless it was worse on several decibels as compared with the performance of systems, which use a separate downconverting channel. It should be noticed actually that a direct comparison is hardly possible due to the systems in consideration distinguish in much more design details than the method of sampling transmitted pulse.

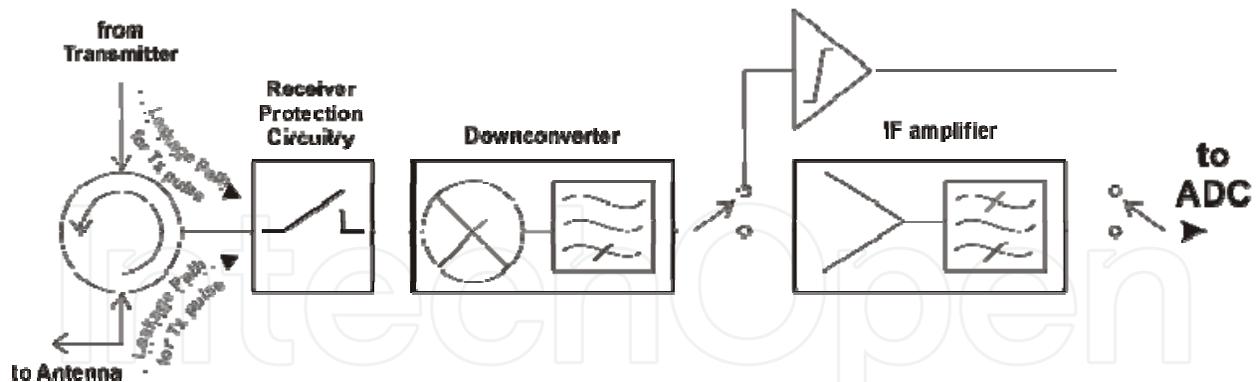


Fig. 11. Utilization of leakage signal to implement coherence-on-receiver technique.

#### 4.3.2 Receiver protection circuitry

As known the magnetron is characterized by a rather high both peak and average power, whereas maximal rated input power of low noise amplifiers (LNA), utilized as the input stage of the radar receiver, is of milliwatt level. Within microwave frequency region a combination of circulator and limiter is the standard de facto solution for providing receiver protection. It may be designed by using only passive circuits. Therefore, no signal is required to control them. It increases reliability considerably. However implementation of similar approach for the radars operating within millimeter wavelength band is complicated due to a lack of suitable limiting diodes accepting kilowatt level peak power. Next, passive limiters allow so-called spikes, which mean that the attenuation provided by such unit may be much less at the front of RF pulse than during its flat part due to a finite forward recovery time of the diode. Evidently the shorter RF pulse front the greater such spikes. Some types of magnetrons, partially the magnetrons with cold secondary emission cathodes is characterized often by a hard self-excitation resulting in a very short RF pulse front duration, which may be of 2-5 nsec only. There are methods to decrease the mentioned spikes in the passive limiters providing, for example, an additional directional coupler and detector in order to bias the limiter diode during RF pulse. However it is hard to find a trade-off between the losses introduced by the biasing circuits and amplitude of the spike. In W band high peak power inherent to the magnetron makes often necessary utilization of two separate antennas for the transmitter and receiver respectively.

The switches based on P-i-N diodes provide better characteristics but nevertheless special approaches should be used to meet above requirements. In order to increase the maximal level of both peak and average power a switch may be build by using multi-diode configuration. It makes its design rather complicated. Another way is to utilize a circulator based switch as it is depicted in Fig. 12, a. A reflective type of P-i-N diodes should be used evidently in the switch. Attenuation in such configuration depends on the isolation of circulator used, whereas insertion losses is determined both by that of circulator and VSWR provided by the diode.

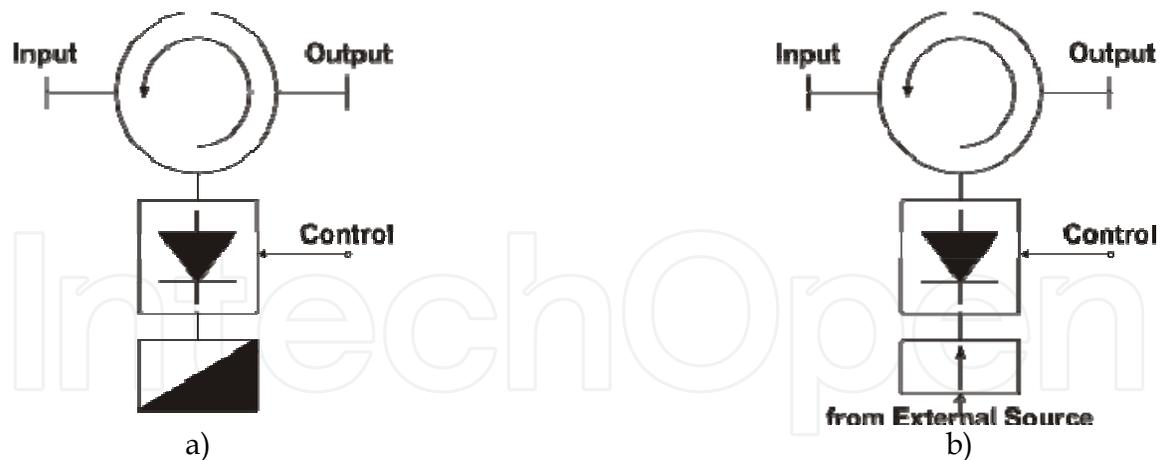


Fig. 12. Design of high power P-i-N switch for receiver protection

Such approach allows us to build an absorptive switch as well as to improve its maximal rated average power due to the incident wave power dissipated on a termination but not on the diode. The parameters of some switches used in Ka band radars (see Section 0) are summarized briefly in Table VII.

The above design of P-i-N switch provides a capability to couple a signal from any external source to its output terminal as depicted in Fig. 12, b. Certainly such configuration of the switch is inferior to that ended by a termination as respect to both an attenuation provided and maximum rated power. However, since the receiver protection circuitry comprises of several switches, a high power rating is not a mandatory requirement for the second and following switches. On other hand there are no additional losses introduced for the external signal. It is important if a noise source is used for the receiver calibration. (see Fig. 10). The output power of such source is low enough requiring a rather high coupling ratio to the receiver input. Evidently, the utilization of passive circuits results in decrease in the radar sensitivity in this case. Certainly there are some disadvantages attending the utilization of above calibration method. Namely, the input circulator and the first protection switch are not inside the calibration loop. Secondly, there is some temperature drift of the calibration introduced by temperature dependency of P-i-N diode characteristics. Nevertheless, the advantages of the above approach are much more meaningful and it can be recommended for wide utilization in the magnetron based radars.

It should be noticed that as follows from Table VII, the most powerful switches, which are capable to handle multi-kilowatt peak power, are characterized by rather low switching speed. It increases the minimal height at which the full receiver sensitivity is achieved. Next, it is rather difficult to provide a tight control of the moment, when the receiver protection switches can be turned on safely. It is due to as mentioned above, in the most modulators there are no circuits to shape the trailing edge of the output pulse in a forced manner, therefore the voltage across magnetron drops rather slowly (see Fig. 7) and duration of this process depends strongly on various parameters. The magnetron is generally characterized by attitude to produce oscillations at rather low anode voltages.

	Switch #1	Switch #2
Bandwidth, MHz	300 MHz	500 MHz
Maximum peak power @ 400 nsec pulse duration, W	> 3500	> 100
Insertion losses, dB	< 0.7	< 0.9
Attenuation, dB	> 25	> 22
VSWR in open state	< 1.2	< 1.3
Switching time @ -3 dB level, nsec	< 1000	< 75
Driving signal	120 mA/-25 V	50 mA/-10 V

Table VII. Parameters of switches of receiver protection circuits operating within Ka band.

These oscillations are weak as usual but may cause LNA damage. A usual way to avoid that is to provide an enough delay before turning the receiver protection switches on. It leads to additional increase in the radar blind zone. The following way is utilized to minimize the response time of the receiver protection system. An additional logarithmic detector is introduced in the channel for sampling the output magnetron pulse (see Fig. 10). Due to its high sensitivity it is possible to detect extremely low level oscillations produced by the magnetron resulting in a tight control of the moment when the switches can be turned on safely. Additionally, by providing two levels detection it is possible to start turning the first – the most powerful and the slowest – switch in advance, at the moment when magnetron is still producing a high but not full power. It allows us to decrease the radar blind zone some more. It should be noticed that there is a very unpleasant effect of the magnetron operation, which affects strongly the receiver safety. Namely, some magnetrons demonstrate the attitude to start producing oscillations not during the front of the modulation pulse but during its trailing edge in opposite. In this case the delay between the triggering pulse and RF pulse may be much longer than usual and it may appear in the moment when the receiver protection circuitry is in a low attenuation state already. Thus such circuitry should process the above condition correctly. In the most of the radars in question if there is no radiation within a definite interval after the transmitter triggering pulse the protection switches remain to be open until next RF pulse.

#### 4.3.3 Receiver dynamical range

A high peak power, which are inherent to magnetron caused not only the above problem while the development of receiver protection circuitry. Another issue is related to maximization of the total receiver dynamical range. Evidently, a high peak power of the transmitter as well as high gain antennas, which can be found in high performance magnetron based radars, lead us to the necessity to introduce rather sophisticated gain regulation circuits in the receiver in order to prevent data loss under either condition. For example, the signal at the receiver input may be as strong as several milliwatts. The total dynamical range for meteorological radars similar to that described in Section 3, should exceed 110 dB. In order to prevent saturation of even the input receiver stage, a regulated attenuator should be used before it. We utilized the following approach. One of the P-i-N diodes of the receiver protection circuitry is driven in the way providing three states, namely, 'off' 'on' '-N dB attenuation' respectively, instead of two states used commonly. It can be achieved by introduction of the corresponding regulation of the current through the diode or the voltage across it. Such way does not require introduction of additional

elements. Despite such approach has proven its usefulness, there were evident disadvantages. At first, the attenuation introduced depends on temperature and frequency rather strongly. Next, every time when the switch is replaced, the corresponding P-i-N diode driver circuits should be re-adjusted in order to keep a standardized attenuation level within allowable margin. An idea to use instead a step attenuator as the third switch (see Fig. 10) looks much more appreciated. However if its implementation seems to cause no serious difficulties in Ka band, for higher frequencies a dedicated development should be done to prove the value of such approach for practical utilization.

#### 4.3.4 Automatic frequency control

Since the transmitter in the radars in question utilizes a free-running magnetron, an automatic frequency control loop (AFC) should be implemented into the receiver in order to tune in it to follow the magnetron frequency. Evidently, AFC should ensure frequency locking over the whole range of possible magnetron operational frequency variation. Next, it should provide a rather good accuracy, especially if an ordinary, non-adaptive matched filtration is used during signal processing.

In early radars AFC design was based on the utilization of analog circuitry including usually some implementation of a frequency discriminator. In this case it is very difficult to meet both above requirements at the same time. Actually in order to achieve a high precision measurement of frequency deviation it is needed to use resonant circuitry with a high figure of merit. On other hand it leads us to decrease in the discriminator operational bandwidth. In addition AFC should operate in a pulsed mode at rather short pulse duration. Moreover, a strong frequency deviation during leading and ending edge of the magnetron output pulse result in additional errors and their dependency on the pulse duration. Nevertheless it was possible to develop AFC on the base of an analog frequency discriminator which demonstrated acceptable performance. The following tricks were used: (i) cropping the input pulse, which reduces the contribution of the frequency modulation during leading and ending edge of the magnetron pulse to the discriminator response; (ii) a periodical throughout calibration of the discriminator circuitry with a dedicated reference signal with the same duration as for the magnetron pulse; (iii) a digital post processing of the rectified output signal of the discriminator including averaging. All above allows us to achieve the long-term AFC accuracy of  $\pm 200$  kHz at the central frequency of 280 MHz and frequency locking bandwidth of  $\pm 150$  MHz independently on magnetron pulse width varying within the range of 100...400 nsec. The above AFC was used in early Ka band meteorological radars (see Section 0).

Continuous progresses in digital signal processing technique and direct integration of the data acquisition system in the receiver have allowed us developing a fully digital AFC circuitry. It comprises of two loops for a rough and fine frequency locking, correspondingly. The first loop is based on direct measurements of the frequency of a downconverted sampled transmitter signal (see Fig. 10) by using an ordinary digital counter. Pulse cropping is used to improve the accuracy as it was described above. This loop works over the whole range of possible magnetron frequency variations and provides the frequency locking accuracy of about  $\pm 1$  MHz at the transmitter pulse duration of 200 ns. The second loop is based on direct measurement of the phase change rate of the downconverted sampled transmitter signal, digitized by an ADC. Due to using a digital quadrature phase detector, the sign of the frequency offset can be measured, and the result of the measurements is

practically independent on the amplitude of the sampled signal. This loop ensures a much better accuracy, which can be as precise as  $\pm 50$  kHz at the output pulse duration of 200 ns, but certainly works within Nyquist range of ADC only.

#### 4.3.5 Signal processing- a few remarks

As known (see Section 0) the magnetron produces incoherent oscillations and only the introduction a corresponding signal processing procedure makes possible retrieving Doppler information. Various techniques can be used to implement such processing, see (Li et al, 1994) for example. Their discussion is not subject of matter of this paper. Nevertheless we would like to notice that a potential provided by the introduction of sophisticated signal processing are not confined by the above possibility. Instead it may change radically our mind on the principles of magnetron utilization. Let us cast a very brief look on that below.

As mentioned above achievable resolution, accuracy and measurement capabilities of any magnetron based radar are related tightly to a particular implementation of sampling of the phase of radiated RF pulse. In principle such sampling can be made in one point of time only and it would be enough to implement Doppler processing in principle. But despite an evident simplicity, this method cannot be recommended due to an inappropriate quality of signal processing inherent generally to it. Instead, in our latest radars we are utilizing another approach based on the measurement of so called phase profile – i.e. set of several measurements of phase in equidistant points of time – for each transmitted pulse. Such profile is used to measure the phase shift between transmitted and received pulse by using convolution and filtration procedures. Since the phase profile is used rather than single phase measurement the following advantages are introduced: (i) a reduction of noise due to inherent averaging; (ii) the effect of intrapulse phase variation as well as the appearance of the frequency offset under downconversion are canceled and do not affect the radar sensitivity and Doppler measurement accuracy – i.e. an adaptive matched filtration is implemented in this case.

The above technique can be used to implement intrapulse frequency modulation capability into magnetron based radar. Actually, it is possible to provide frequency chirp by varying the magnetron anode voltage during the modulation pulse. Then a digital technique may be utilized to calculate a correlation function for each radiated pulse and utilize a compression-like processing in order to increase the radar spatial resolution. Namely the millimeter wave magnetrons allow attaining a relatively wide frequency chirp without a significant variation of its output power. For W band magnetrons it is possible to achieve 100 MHz frequency chirp. In the case of successful implementation of the above approach, a considerable improvement both in the radar resolution and sensitivity may be expected.

Next, above we described the successful implementation of precise measurement of the magnetron frequency for every radiated pulse (see Section 0). Fundamentally, the utilization of a similar technique allows us to expect a considerable improvement of Doppler processing quality in radars equipped with non-coaxial magnetrons as well as to reduce requirements for the stability of the voltage pulse across the magnetron. Actually, the usage of a high resolution ADC increases greatly the precision of frequency measurement. Certainly we mean relative measurements. We expect that for 200 ns pulse length the achievable accuracy may be as lower as 1 kHz that corresponds to relative accuracy of  $3 \cdot 10^{-8}$  and  $10^{-8}$  for Ka and W band magnetrons respectively. The indicated value is on about order better than the best frequency stability achieved (see Section 0) resulting in the

corresponding improvement of Doppler processing quality. Certainly sophisticated algorithm should be developed to avoid influence of noise, intrapulse frequency modulation etc on the frequency measurements accuracy. This approach is important especially for W band magnetrons, which frequency stability is much less than for Ka band devices and coaxial devices are not produced at all.

## 5. Conclusion

The above discussion demonstrates clearly that the utilization of recent advances in magnetron manufacturing technology, the introduction of novel approaches in radar design as well as a vast progress in digital signal processing technique result in a solid overall performance of the magnetron based millimeter wavelengths radars. A number of such radars developed and manufactured by our institution, which have been put into operation during last several years as well as the experience of their utilization allow us to claim for a great potential of the magnetrons for the radar development. We dare to affirm that a rather inveterate opinion about futility of such devices to built contemporary radar systems should be considered to be expired.

An evident room for ulterior improvements in both developing high voltage modulators ensuring tighter control of the magnetron operation and introducing sophisticated signal processing algorithms make possible to expect even higher performance level of the magnetron based radars, especially for that operating within short millimeter wavelength bands in the nearest future.

## 6. Acknowledgments

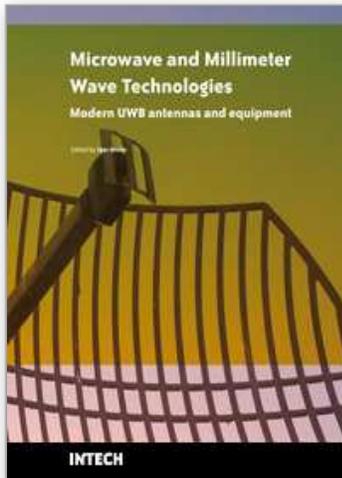
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