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Microwave cyclotron protective devices for radar receivers

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Abstract: **Brief overview of the latest developments of microwave cyclotron protective devices, their functioning and parameters is given. It is noted that these devices have a number of important advantages over other types of protective devices: they are autonomous, provide no peak of microwave power leaking to the output, frequency filtering and low noise figure (0.7-1.2 dB). The upper limit of the linearity of cyclotron protective devices in the signal transmission mode when the transmission coefficient is compressed by 1 dB is ~ 1 mW. The devices can operate with an input pulse power of up to 10 kW or more, while the attenuation of the input power in the protection mode is more than 60-80 dB. The recovery time of parameters after the end of a powerful input pulse is 10-20 ns. For devices of the 3-cm wavelength range, experimental data are given on the recovery time, the upper limit of linearity, attenuation of the input power in the protection mode, and filtration characteristics.**

Keywords: **cyclotron protection device, tape electron beam, fast cyclotron wave, peak leakage power, recovery time, noise figure**

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Contents

1. INTRODUCTION

The parameters of modern radar systems are determined by the design features and characteristics of antennas and devices for generating emitted signals and their element base [1]. Of no less importance for the operation of the radar is the processing of the received signals reflected by the target. A very important role in this process belongs to the protective device for the radar receiver. The task of the device is to protect the sensitive input stages of the receiver from the impact of a powerful pulse of transmitter (usually up to 10% of the power of the emitted pulse is reflected from the antenna and enters the input of the receiver), as well as from the targeted electromagnetic influence of extraneous electronic suppression means [2].

Over the past 20 years, cyclotron protective devices (CPD) have become quite widespread in new Russian developments of microwave radars, as well as cyclotron-protected complexed amplifiers (CPCA), which are a combination of a CPD with a low-noise transistor amplifier (LNA) and additional service devices. Radars with active phased antenna arrays are not considered in this case.

The main properties of the CPD and their advantages over other types of protective devices (gas-discharge, semiconductor and others) are as follows:

- CPD is an autonomous protector, i.e. passes from the signal transmission mode to the protection mode and back without a control signal;

- there is no peak of the microwave power leaking to the output in the CPD, which usually occurs in other types of protectors at the moment of the leading edge action of a powerful input pulse;
- due to the specifics of the interaction of the CPD resonators and the electron beam the device performs the functions of a frequency filter;
- CPDs are capable to operate with an input pulse power up to 10 kW and more, while the attenuation of the input power in the protection mode is 60-80 dB and more;
- CPD recovery time after the end of a powerful pulse at the input is 10-20 ns;
- CPDs have low noise figure (0.7-1.2 dB) in signal transmission mode;
- the upper limit of the CPD linearity in the signal transmission mode with compression of the transmission coefficient by 1 dB is 0.5-3 mW, when the input power increases by 3-5 dB more the device goes into protection mode.

Let us consider the basic principles of the CPD operation.

2. DESIGN AND PRINCIPLES OF WORK

CPD is a vacuum electron beam low noise microwave device of the O-type with transverse interaction, the operation of one based on the excitation of a fast cyclotron wave (FCW) in an electron beam [3-6]. CPD continues the line of low noise electron beam parametric amplifiers (EPA) and electrostatic amplifiers (ESA), developed in the 60-80s of the 20th century. EPA also known as Adler tube. Relativistic effects during the operation of the devices are negligible.

In **Fig. 1** shows the functional diagram of the CPD in the transmission mode. The electron gun (1) forms a tape electron beam (2), which sequentially passes through the input resonator (4), the dividing section (5), the output resonator

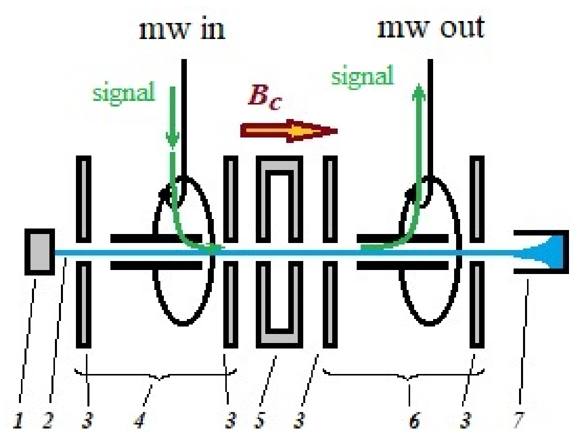

Fig. 1. *Functional schema of the CPD in the transmission mode.*

(6) and settles in the collector (7). The input and output resonators in the plane perpendicular to the beam axis are closed on both sides by disks (3). The input resonator, the dividing section, and the output resonator form the electrodynamic system of the CPD is located in a longitudinal uniform magnetic field Bc, which provides cyclotron resonance of electrons at the operating frequency.

The input and output resonators of the CPD are resonators with an extended capacitive gap, the so called Cuccia resonators (Cuccia couplers) [7,8]. The transverse dimension of the electronic gap is from 0.1 mm to 0.25 mm for the CPD of various frequency ranges. The gap length is such that the electron makes several cyclotron revolutions in the cavity. A tape electron beam is emitted by an oxide microcathode with an emission surface of 0.02 mm by 0.7 mm; the beam current is from 150 μA to 250 μA. The CPD uses a shielded-type magnet system with a samarium-cobalt permanent magnets and thermal stabilization based on thermomagnetic shunts.

CPD in the transmission mode works as follows: FCW is excited in the beam in the input resonator due to the signal energy (transverse oscillations of electrons with added energy at the cyclotron frequency) and transferred by the beam to the output resonator, where it is removed from the beam and transmits to the output of the CPD. When a signal wave is excited, electron bunches do not appear in the beam; for this reason, the signal transmission is linear up to the input power level (~1 mW), at which the deposition of electrons begins on the walls of the electron gap due to an increase in the amplitude of transverse oscillations.

Since the operation of the device is based on interaction with a fast wave of an electron beam, this makes it possible to remove thermal noise from the signal wave in a passive coupler (input resonator) simultaneously with the introduction of the signal power into the FCW. This mechanism allows you to achieve a fairly low intrinsic noise figure (0.7 ... 1.2 dB). The working frequency band of the CPD is determined by the band in which the conditions of complex-conjugate matching of the conductivities of the electron beam, the resonator itself, and the external load are fulfilled at an acceptable level.

When the input microwave power increases to a level above several mW, the electron beam destroys in the input cavity. The input and output resonators will be separated from each other by a dividing section, while the power from the input resonator to the output one can only be transmitted through the electron beam opening in the dividing section with significant attenuation.

As is known, classic autonomous protective device is a high frequency line connecting the input and output, which includes gas discharge, semiconductor (pin-diode) or other devices, the impedance of which decreases sharply and significantly with an increase in the transmitted power to a certain level (see **Fig. 2**).

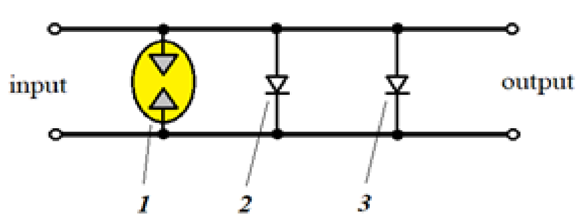

Fig. 2. *Functional schema of a classic microwave hybrid protector.*

In Fig. 2, numbers indicate: 1 – gas discharge protection element, 2 and 3 - pin-diode stages of the protector. With a sufficiently steep leading edge of a high level power pulse falling on the protector, at the initial moment of time, until the gas discharge in the element (1) ignites and the pin-diodes (2) and (3) open, the input microwave power is supplied to the output of the protector. In this case, a peak of leakage power forms at the output of the device.

There is no single high frequency line connecting the input and output in the CPD. At the moment the CPD transits from the transmission mode to the protection mode, the peak power at the output of the device corresponds to the maximum energy capacity of the electron beam on the verge of its destruction.

In the protection mode, the input resonator is not loaded with an electron beam and is mismatched with the input line (VSWR of CPD input ≈30), for this reason up to 90% of the microwave input power reflects from the CPD input. The remaining power dissipates in the input line and the input resonator as heat.

3. ELECTRICAL PARAMETERS

The working frequency band of the CPD as well as the frequency parameters of filtering the input signals (see **Fig. 3**) are determined by the active and reactive conductivities of the electron beam in the gap of the Cuccia resonator near the cyclotron frequency [4,8] and the degree of their matching with the conductivities of the resonator and external loads as above.

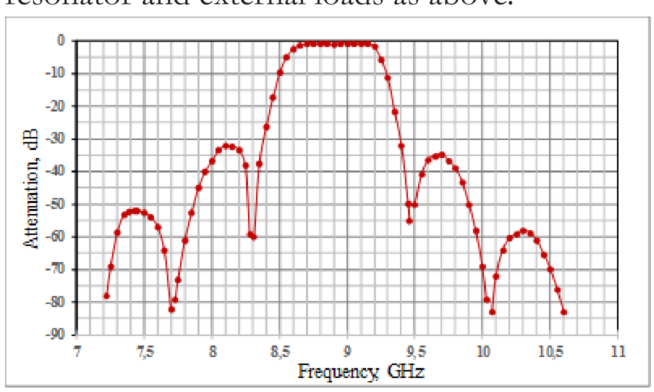

Fig. 3. *An example of the transmission coefficient of a CPD in a wide frequency band.*

Dips in the transfer coefficient (Fig. 3) correspond to the frequencies of detuning from cyclotron resonance in the angle of flight of electrons in the resonator gap by $2\pi n$, where $n = \pm1, \pm2,\ldots$ [4,8]. Physically, this is explained by the fact that the longitudinal axis of the electron beam (the axis on which the centers of mass of electrons in each cross section of the beam are located), upon excitation of the FCW at frequencies other than the cyclotron frequency, takes the form of a weakly twisted spiral. At the frequencies of the transmission coefficient dips, the indicated "spiral" of the electron beam axis along the length of the resonator has an integer number of turnovers; for this reason, the cyclotron rotation of the beam in the resonator gap does not induce a current in it (for each electron there is another electron within the resonator oscillating in antiphase with it).

The filtering properties of the CPD play an important role in suppressing side reception channels in the radar receiving devices [9].

The transition of the CPD from the transmission mode to the protection mode is associated with an increase in the input microwave power, an increase in the radius of rotation of the beam electrons and their settling on the walls of the electron gap in the input resonator. As the input power increases, the edge electrons of the beam first begin to settle, the transmission coefficient of the CPD decreases, the linearity of the transmission coefficient violates, and the beam current reaching the collector decreases [10].

The total power received from the field by all beam electrons located in the cavity gap can be obtained from the expression:

$$P = \frac{I_0}{2(e/m)}\omega_c^2 R^2, \qquad (1)$$

where I_0 is the beam current, ω_c is the circular cyclotron frequency (corresponds to the center frequency of the operating frequency band), R is the radius of the cyclotron rotation of electrons, e is the charge and m is the electron mass. Based on (1), it is possible to estimate the power at which the edge electrons of the beam begin to settle: $P_{\rm lim} \approx -4$ dBm (frequency is 9 GHz, beam current is 200 μA, gap between the beam and the gap wall is 15 μm), which is in good agreement with the experimental data in the **Fig. 4.** The decrease in the current passing to the collector by a factor of 1.26 (corresponds to –1 dB) coincides with the input power, at which there is a compression of the CPD transmission by 1 dB: $P_{-1\rm dB} \approx 3$ dBm. The input power attenuation in protection mode is ≈ 75 dB.

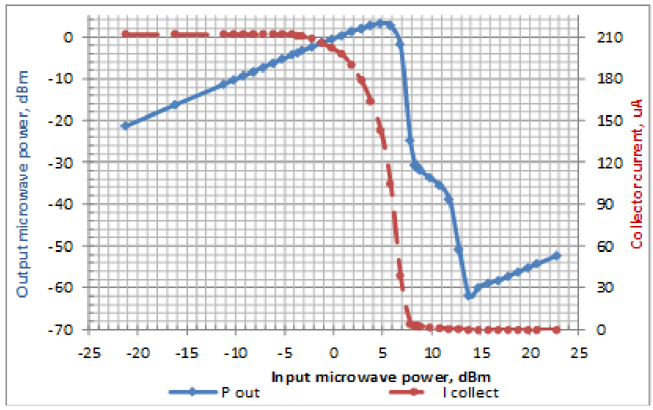

Fig. 4. *Linearity boundary and transition to the protection mode of the CPD for a wavelength range of 3 cm.*

The maximum power supplied to the output of the CPD during the transition to the protection mode does not exceed 4-5 mW, for higher frequency CPDs – 8-10 mW, for low frequency CPDs – 1 mW.

One of the main advantages of a CPD is a short recovery time. Taking into account the high mobility of electrons in vacuum, the recovery time of the CPD is determined by the time of decreasing the amplitude of electromagnetic oscillations in the low-Q input resonator caused by the action of the input power pulse, and the time of flight of the electron beam between the input and output resonators. At the initial stage (stage 1) of restoring the signal transmission, the resonator is loaded with an external load and its own losses (typical resonator Q-factor $Q_1 \approx 25$). At the next stage (stage 2), the passage of the beam in the gap restores and, accordingly, the Q factor of the resonator decreases from the level Q_1 to the maximum loaded level $Q_3 \approx 8$ (stage 3 – the passage of the beam and the signal is restored). The figure of merit averaged over the transient stage 2 can be assumed to be $Q_2 \approx 16$.

As known, the time of decreasing the amplitude of oscillations in a circuit with a quality factor Q from the power level P_1 to the level P_2 determines by the expression:

$$t = \frac{Q}{2\pi f} \ln \frac{P_1}{P_2}, \qquad (2)$$

where t is the time of decreasing the amplitude of oscillations, f is the frequency of oscillations.

For a wavelength range of 3 cm, estimates from expression (2) at typical power levels shown in Fig. 4 give the following values: the duration of stage 1 is $t_1 \approx 4$ ns for an input pulse power of 1 kW and $t_1 \approx 5$ ns for an input pulse power of 10 kW (90% of the microwave input power is reflected from the mismatched resonator). The duration of stage 2 is $t_2 = 0.6$ ns.

With a typical time of flight of electrons between the centers of the input and output cavities of 2-4 ns, the recovery time of the CPD in the 3 cm wavelength range will be $t_r \approx 10$ ns. In the wavelength range of 10 cm, the recovery time of the CPD is $t_r \approx 22$-26 ns.

For an additional time from 3 to 10 ns (the duration of stage 3, depending on the frequency range), the maximum sensitivity in the CPD corresponding to a noise figure of 1-1.5 dB is restored.

In the present estimates of the recovery time it is assumed the ideal trailing edge with zero duration of a powerful input microwave pulse.

As noted above, most of the high level input microwave power reflects from the mismatched resonator. To ensure an extremely short recovery time of the device the reflected power should be directed into the load for prevent its re-reflection from the elements of the antenna-CPD path and the input of the CPD. **Fig. 5** shows the oscillograms of the microwave energy reduce at the CPD output

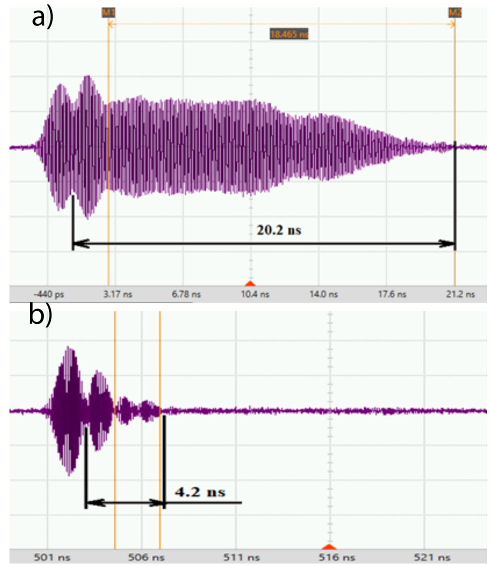

Fig. 5. *Oscillograms of the recovery time of the CPD in the wavelength range of 3 cm: a) without a ferrite valve at the input, the length of the connecting cable between the generator and the input of the CPD is 0.9 m; b) a ferrite valve is connected to the CPD input.*

at the end of an input pulse with a power of 23 dBm with a cutoff duration (trailing edge) of a pulse of 0.5 ns. Fig. 5*a* - the duration of the reduction process of 20.2 ns is due to the propagation of the power reflected from the CPD input to the generator of a powerful signal, followed by reflection of the power from the output of the generator and its re-entry to the input of the CPD with the length of the connecting cable 0.9 m. The swelling on the oscillogram to the left of the 20.2 ns time interval is due to the passage of the input pulse cutoff through the CPD (the left border of the 20.2 ns time interval on the oscillogram separates the modes of operation of the CPD: on the left – the mode of protection against the input pulse, on the right – the transmission mode in the absence of an input pulse. Figure 5b – similarly for 4.2 ns interval).

The use of a ferrite valve directly at the input of CPD (Fig. 5*b*) makes it possible to exclude the re-reflection of the microwave power in the path generator-CPD and to observe the proper recovery time of the CPD, in this case 4.2 ns.

4. CONCLUSION

CPD is a very attractive device for use in radar receivers due to the physical principles on which its work is based:

- interaction with the fast wave of the electron beam allows to remove thermal noise from the beam in the coupling resonator and achieve a low noise figure;
- interaction with a transverse (cyclotron) wave does not lead to the formation of electron charge bunches in the beam and provides a high linearity of the device;
- work with an electron beam in a vacuum – the use of charged particles with maximum mobility – allows to achieve an ultra-short recovery time of the protective device;
- connection of the input and output of the CPD in the transmission mode through an electron beam ensures the absence of a leakage peak power.

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