# A NEW CLASS OF SELF-PROTECTING LOW-NOISE MICROWAVE AMPLIFIERS

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## ABSTRACT

The ESA (electrostatic amplifier) was originally developed by Robert Adler in the United States and independently by S. P. Kantyuk in the Soviet Union. It has been developed and extended at ISTOK to a family of devices having some unique properties. ESA's can provide low noise figures (1...4 dB from L- through Ku-bands), wide dynamic range, high resistance to jamming, linear amplitude and phase characteristics, and the ability to handle high levels of input power (up to 500 kW) without additional protection. In radar applications no additional protective devices such as multipactors, gas discharge T/R tubes, diode limiters, or switches are required. The recovery to maximum sensitivity after an input overload is typically 10-50 ns. These devices have been combined with magnetron oscillators to provide compact transmitters and are widely used in ground-based pulse-doppler radar systems.

## INTRODUCTION

The Research and Production Corporation ISTOK has been developing low-noise electron-beam microwave amplifiers based on cyclotron resonance, referred to as ESA's (electrostatic amplifiers), for a number of years.

ESA's have a unique combination of characteristics, specifically: low noise figure, wide dynamic range, linear amplitude and phase characteristics, low noise levels in the doppler frequency range and self protection from, and the ability to rapidly recover from, high input overload levels. This is particularly important in pulse doppler radars where protection of the input stages from transmitter leakage and rapid recovery are important system considerations.

Production ESA's have been developed at frequencies from 0.4-14 GHz. The corresponding noise figures range from 0.7 to 4 dB. In order to increase gain, ESA's have been developed with an integral transistor amplifier; such a device is called an ESCA (electrostatic combined amplifier).

Unique hybrid devices called "potentialotrons" have been developed which combine the functions of a power pulsed oscillator, low-noise amplifier and a rapid transmit-receive switch. Potentialotrons are a combined magnetron and ESA; the resonant system of the magnetron and ESA input resonator have common microwave energy output-input and common magnetic systems.

## ESA DESIGN AND MAIN CHARACTERISTICS

A simplified schematic representation of an ESA is shown as Figure 1. An electron stream formed by an electron gun drifts in a longitudinal magnetic field and sequentially passes through the input resonator, amplifying structure, output resonator, and passes into the collector.

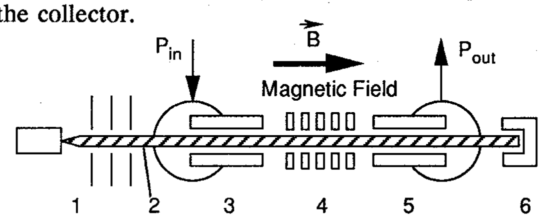


Figure 1. Simplified Diagram Of An ESA. 1-Electron Gun; 2-Electron Beam; 3-Input Resonator; 4-Amplifying Structure; 5-Output Resonator; 6-Collector.

The input resonator is a cavity resonator with an extended gap, as shown in Figure 2. The input signal energy is coupled into the electron beam in such a manner as to induce cyclotron motion of the electrons. This transfer takes place when the input signal frequency $\omega_s$, the electron cyclotron rotation frequency $\omega_e$, and the input resonator resonant frequency $\omega_r$ coincide.

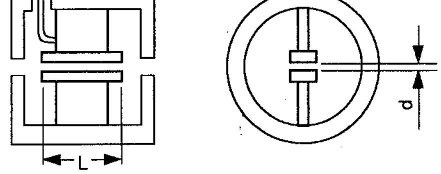


Figure 2. ESA Resonator, where L Is The Resonator Segment Length And di Is The Resonator Gap.

An exponential growth of transverse oscillations of the electrons takes place in the periodic electrostatic structure when the cyclotron oscillation of the electron beam coincides with the periodic electrostatic field generated by the amplifying structure. The growth of the transverse oscillations is due to a corresponding slowing of electrons in longitudinal direction; the total electron energy is conserved during the amplification process.

The design of the output cavity is similar to that of the input cavity. It couples energy from the beam and makes it available to the output load.

A crucial requirement for ESA operation is a carefully controlled magnetic field. The required strength of the field is determined by cyclotron resonance conditions, and it must have a high degree of spatial homogeneity and time stability in the area of the input and output resonators and the amplifying structure.

Early ESA designs used solenoidal electromagnets, which provided a magnetic field having the required characteristics. Unfortunately such electromagnets were heavy, large, and inefficient. Since these difficulties increase with frequency, ESA's with solenoid electromagnets were primarily developed at frequencies below 3 GHz.

More recent designs utilize samarium-cobalt permanent magnets, and many of these limitations have been overcome. Using permanent magnet focusing overall power consumption has been reduced to 1-1.5 watts, and the amplifier mass is from 2-4 kg for units operating as high as 14 GHz.

## PERFORMANCE PREDICTIONS

ESA gain $K_g(\omega_g)$ is a function of transfer coefficients of input $(K_{in}(\omega_s))$ and output $(K_{out}(\omega_s))$ resonators and the electron gain $K_{eg}$ in the electrostatic structure:

$$K_g(\omega_s) = K_{in}(\omega_s) * K_{eg} * K_{out}(\omega_s) \quad (1)$$

since $K_{eg}$ is largely independent of signal frequency, the frequency characteristics $K_g(\omega_s)$ are defined primarily by the input and output resonators. For wideband operation it is desirable to increase the electron flow to broaden this bandwidth. The conductance at cyclotron frequency is defined as follows:

$$G_o = \frac{I_o * L^2}{8 U_o * d^2} \quad (2)$$

where $I_o$ is the electron beam current, $U_o$ is the voltage at the resonator body, and L and d are the length and width of the capacity gap of Figure 2. All parameters in equation (2) are interrelated, and in practice increasing $G_o$ is a complicated task.

Currently, values of $G_o \approx 2*10^{-3}$ I/Ohm are realized in ESA's, allowing operating frequency bands of 5-7%. For these amplifiers an electron beam microperveance of 10 $\mu A/V^{3/2}$ has been achieved, which is a record value even for power microwave oscillators.

The ESA minimum noise figure is determined by the cathode temperature, the relation of magnetic field intensity on the cathode ($B_c$) to the field intensity in the area of signal gain ($B_g$), and signal losses in the input resonator. The minimum noise figure is:

$$NF_{min} = \frac{1}{\eta_{in}} \left(1 + \frac{T_c}{N * T_o}\right) \quad (3)$$

where $\eta_{in}$ is the input resonator efficiency (0.95 - 0.98), $T_c$ is the cathode temperature (≈ 1000°K), $N = B_c/B_g$, and $T_o$ is room temperature (300°K). From equation (3) it follows that when N=20 (which can be achieved for ESA's at frequencies up to 3 GHz), $NF_{min} = 1.23$ units or 0.9 dB. In the 10 GHz range for N=6 and $\eta_{in} \approx 0.95$, $NF_{min} = 1.73$ units (2.4 dB). These values of noise figure were achieved in practice.

The ESA is unique among extremely low-noise amplifiers in its ability to function without additional protective devices to protect the input from high-power overloads. Therefore, the ESA noise figure almost completely defines radar receiver sensitivity.

The maximum allowable microwave power level in the amplifier input is determined by the electric strength of the ESA input circuit and the breakdown of the capacity gap of the input resonator. As was mentioned above, the input resonator efficiency is typically 95-98%, which corresponds to a "cold" (without electron flow) VSWR of the input resonator of 20-50:1. Figure 3 gives frequency dependence of "cold" and "hot" (with electron flow) VSWR of the input resonator.

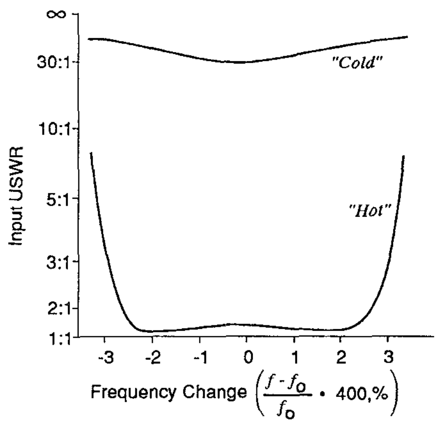


Figure 3. Input Resonator VSWR As A Function Of Frequency.

When the input power is in the limits of the ESA dynamic range (up to -20 dBm), low values of VSWR are realized in the operating frequency band, and all input power is absorbed by electron flow. For input power of ≈2-5 mW the electron flow is intercepted by the input resonator and the input VSWR reaches its "cold" value. For this condition almost all of the input power is reflected. Since the resonator transition from "cold" condition into the "hot" one is caused by electron flow, the switching time is extremely short ( ≈ 1 ns). The ESA maximum sensitivity recovery time is almost completely defined by the time for the stored energy in the input cavity to decay from the maximum amplitude value to the level of thermal noise. This time is:

$$U(t) = U_{max} Exp\left(-\frac{\omega_s t}{2Q_n}\right) \quad (4)$$

where $U_{(t)}$ is the voltage of the resonator and $U_{max}$ is the peak voltage of the resonator capacity gap, t is time, and $Q_n$ is the resonator loaded quality factor.

To illustrate achievable values of recovery time, consider an approximate expression obtained from equation (4):

$$\tau_{rec} = \frac{Q_n}{6.28 f_s} \ln \frac{4 P_{pulse}}{\delta \sqrt{P_{dep} * P_{1in}}}, \quad (5)$$

where $f_s$ is the signal frequency (GHz), $\tau_{rec}$ is the recovery time (ns), $P_{pulse}$ is pulsed power in Watts ($\approx 10^4$W), $P_{dep}$ is the power at which the whole electron flow is intercepted by the input resonator ($\approx 5*10^{-3}$W), $P_{1in}$ is the maximum input power in linear amplification mode ( $\approx 10^{-5}$W), $\delta$ is the resonator "cold" VSWR (≈30:1). Using these values, $\tau_{rec}$ = 4 ns for 10 GHz operation.

**SAMPLE ESCA**

Figure 4 is a photograph of an Electrostatic Combined Amplifier which operates from 7-7.4 GHz. The unit contains an integral voltage divider to supply the electrostatic potentials and requires a single high-voltage (400 V) supply for operation in addition to small filament and transistor amplifier supply voltages.

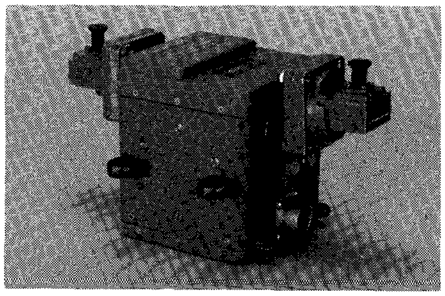

Figure 4. Photograph Of A Representative ESCA. This Unit Operates From 7-7.4 GHz.

The unit has a noise figure of 3.4 dB and a gain of approximately 23 dB. It can withstand in excess of 5 kW peak and 150 W average power at the input and recover in less than 50 ns. The maximum input signal for normal operation is -20 dBm, but there is a control voltage which can reduce gain by 10 dB, permitting operation to -10 dBm input power levels. Figure 5 presents the transfer function of the ESCA, illustrating the self-protection characteristic of the unit.

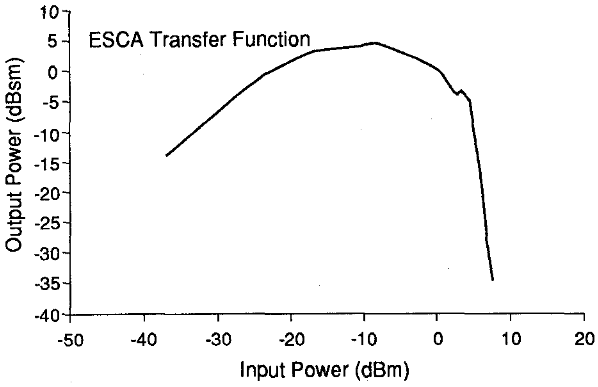


Figure 5. Transfer Function Of An ESCA. Note The Self-Protecting Behavior For High Input Levels.

**CONCLUSION**

This paper has provided an approximate representation of physical processes and ESA design features. The complete ESA theory is rather complicated and far from complete. Nevertheless, at present these amplifiers show good performance in several modern radars.