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# THE USE OF p-i-n DIODES IN NUCLEAR ELECTRONIC CIRCUITS

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## Introduction

Two important fields of p-i-n diode applications are generally known. At high frequencies (1 GHz and more) the p-i-n diodes are used to control microwave power. Various circuits using p-i-n diodes were developed, for example, microwave power switching circuits, phase shifters, attenuators and modulators. At very low frequencies (less than 1 kHz) the p-i-n diodes are used as power rectifiers with the superb low frequency rectification characteristics.

This work deals with p-i-n diode application in nuclear electronic circuits for nanosecond and subnanosecond range, with the corresponding frequency range of several megahertzes to several gigahertzes. In such a case, rather different characteristics are desirable, than in two fields mentioned above. No extreme values of the peak power or peak current transmission and breakdown voltage are demanded. The smaller dependence of the capacitance on the forward bias d.c. current and the smaller diode losses at the zero bias at high frequencies would be desirable from the diodes.

The measurements of diode characteristics and testing of circuits were performed with the p-i-n diodes appointed for work in 9 GHz band. The results obtained confirm the possibility of p-i-n diode use in nuclear electronic circuits for the nanosecond and subnanosecond range.

## 2. General Characteristics of the Diode

The p-i-n diode structure and the equivalent circuit of the diode with parameters independent on the frequency are shown in fig.1A /1/ . The diode consists of a thin slice of high resistivity, intrinsic semiconductor material i with heavily doped p and n regions of very low resistivity on either side /1-3/. In the real case, the intrinsic region has a slight donor or acceptor concentration and behaves as a slightly lossy dielectric with $\pi$ or $\nu$ type conductivity. Heavily doped regions behave as good conductors.

The distribution of donnors and acceptors in p,i and n regions together with the area and thickness of the i region results in rising of an exhaustion region j, space charge region in the diode. The exhaustion region in zero-bias state occupies practically all the intrinsic region and determines the nature of the p-i-n diode.

The mechanism of p-i-n junctions can be described qualitatively with the help of characteristics that can be effected by reverse and forward bias.

When the diode is biased in reverse direction and reverse voltage increases, the exhaustion region widens and occupies all the intrinsic region. In such a case, the value of the diode resistance is very high. Simultaneously the effective shunt capacitance of the diode is very small, independent of reverse bias voltage. The impedance of the diode at high frequencies is essentially capacitive. The voltage breakdown of the reverse biased diode depends on the thickness of the i-region and can be very high, of the order of $10^3$ V. The simplified equivalent circuit of the diode in reverse bias state is shown in fig.1B.

When the diode is biased in forward direction and forward bias voltage and forward diode d.c. current increase, the exhaustion region shortens. The intrinsic region begins flooding with injected carriers and the resistivity of the diode rapidly decreases. In forward bias the capacitance component of the diode is remarkably small and the impedance of the diode at high frequencies is essentially resistive. The value of the diode resistance depends on the d.c. current and can be varied over a large range, being very high for zero bias and very low, of the order of $10^{-1}$ ohms, when d.c. current, for instance 100 mA flows through the diode in the forward direction. The simplified equivalent circuit of the diode in forward bias state is shown in fig.1C.

The values of the p-i-n diode equivalent circuit components presented for backward and forward bias states are summarized in table 1. The values were reported in works /1,3/. The important characteristic of the diode operated in pulse circuit is the maximum pulse width or minimum frequency at which the signal can be transmitted without pulse shape distortions. This characteristic depends on the charge stored in the intrinsic region of the diode biased in forward direction. The switching time necessary to remove the stored charge from the intrinsic region depends on the area and thickness of the intrinsic region, and on the forward bias d.c. current, and the amplitude of the pulse applied as well. Switching time of the p-i-n diodes can be of the order of $10^{-6}$ - $10^{-3}$ s. The resistance of the diode remains low and constant as long as the stored charge is not completely removed. Therefore the p-i-n diode can also transfer pulses in the wide dynamic range of pulse amplitudes, without non linear distortions.

## 3. Measurements of the Diode Characteristics

The performance of p-i-n diodes was tested both in small-signal and pulse operations. The pulse measurement of p-i-n diodes was performed in the real circuit, diode attenuator-invertor. The results of pulse measurement are summarized in the next section, in short specifications.

Small-signal measurement was performed to find the diode equivalent circuit components. The p-i-n diode-twins were used as the variable resistances in our circuits therefore the diode-twins were measured and the equivalent circuit components wer determined as functions of the forward bias d.c. current and the frequency. The p-i- diode-twin was mounted into the cartridge and measurements were performed with associated circuits for the diode biasing, analogically to the operating conditions in the rea circuits. The frequency range was chosen 30-900 MHz corresponding to the pulse spectru in nanosecond and subnanosecond range.

The results of the small-signal measurements are indicated in Smith chart form in fig.2. The impedance of a diode-twin is plotted as a function of the d.c. current an the frequency. The resistance and capacitance of the parallel equivalent circuit were calculated and the values R and C are plotted as a function of the forward bias d.c. current in figs. 3,4.

The results obtained show that the value of the capacitance can be treated as the frequency independent parameter within the used frequency range. The value of the resistance for slightly forward biased diode is a parameter dependent on the frequency due to the dielectric loss in the diode. The diode loss can be represented by the loss resistance, which parameter was found to be independent of the forward bias d.c. current. Within the experimental errors, the diode resistance can be composed from two resistance components connected parallelly: the loss resistance and the approximate d.c. resistance (dashed line in fig.3).

### 4. Diode Application in Pulse Circuits

The p-i-n diodes were used as the continuously variable resistances in the attenuators of the P-network or Bridge-network types, where the resistors were replaced in individual branches by the diode-twins. The simple calculation based on the use of diode characteristics reported in the previous section proves that the attenuation, the reflection and the characteristic impedance of the attenuator can be maintained in reasonable limits, within the frequency range corresponding to the transmitted pulse spectrum.

In both P and Bridge-attenuators, the attenuation is controlled by the diode forward bias d.c. currents. The P and Bridge-attenuators were mounted into the coaxial line and connected to the pulse generator and oscilloscope. The corresponding values of the attenuation and the currents $I_1$, $I_2$ (fig.5, fig.6-curve A) were adjusted exprimentally, provided the minimum reflections. The pulse of an 1.4 nsec risetime and 100 nsec pulse width FW (0.9) M was used for calibration.

The following circuits appointed for work in the input stages of the nuclear pulse discriminators with high input signal resolution were developed. The diode attenuator -invertor (fig.7A) connected with the fixed threshold discriminator can be used as a fast integral discriminator. The diode attenuator bifurcation (fig.7B) connected with two fixed threshold discriminators and associated anticoincidence circuit and output pulse standardizer can be used as a fast differential discriminator /4,5/ The diode bipolar pulse shaper connected with the true zero-crossing discriminator can form a pulse shaper using the constant fraction of pulse height technique.

In all these applications the basic circuit diode attenuator-invertor (fig.8) was used. It consists of the following functional parts: the asymmetric-symmetric transformer, the controlled diode bridge, the output symmetric-asymmetric transformer, and the control circuit for the continuous adjustment of the diode bridge attenuation. The values of the currents $I_1$, $I_2$ adjusted by means of the control circuit are shown in fig.6-curve B.

The performance of the diode attenuator-invertor is demonstrated by the waveforms analogous to the scintillation pulse, shown in figs.9, 10 which represents the input pulse and the output pulse distortion after 40 dB attenuation.

The calibration of the attenuator was performed with rectangular pulses of 100 nsec FW (0.9)M and 1.4 nsec risetime. The dynamic range of input pulse amplitudes was 100 mV-100 V. The results are summarized in short specifications:

Diode attenuator-invertor
- Input: Negative or positive rectangular pulse
  - Risetime: 1.4 ns
  - Pulse width: 100 ns FW (0.9) M
  - Dynamic range: 100 mV - 100 V
- Output: Negative or positive rectangular pulse
  - Risetime: < 1.6 ns
  - The difference between leading edge 90% point and trailing edge 90% point: < 5%

Characteristic impedance: 100 ohms
Attenuation: 6-52 dB continuously
Reflections: < 26 dB
Feedthrough: <52 dB

Diode attenuator bifurcation
- Input and output specification is the same as the specification of the diode attenuator-invertor.
- Input characteristic impedance: 50 ohms
- Output characteristic impedance: 100 ohms
- When attenuation is varied in one of the two channels, the variation of the output pulse amplitude in the second of the two channels is less than 2%.

Diode bipolar pulse shaper
- Input: Negative or positive P.M. pulse
- Input characteristic impedance: 50 ohms
- Output: Bipolar pulse, produced by the linear attenuation-subtraction technique
- Zero-crossing point: continuously variable, corresponding to the leading edge point at the 1-50% level of the P.M. pulse height
- Output characteristic impedance: 50 ohms
- Attenuation: 6 dB

## References

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Table I

| Backward bias.<br>Reverse voltage increases from 0 to 100 V | Forward bias.<br>Forward diode d.c. current increases from 0 to 100 mA |
|---|---|
| $R_{sp} \doteq R_{sn} \doteq 10^{-1}$ ohms | $R_{sp} \doteq R_{sn} \doteq 10^{-1}$ ohms |
| $R_i$ decreases from $10^3$ ohms to 0. | $R_i$ decreases from $10^3$ ohms to $10^{-1}$ ohms |
| $C_i$ increases from $10^{-1}$ pF to $\infty$. | $C_i$ increases to $10^1$ pF |
| $C_d \doteq 10^{-2}$ pF | $C_d \doteq 5.10^{-1}$ pF |
| $R_j \doteq 10^9$ ohms. | $R_j$ decreases to $5.10^{-1}$ ohms. |
| $C_j$ decreases from $10^0$ pF to $10^{-1}$ pF | $C_j$ increases to $10^1$ pF |

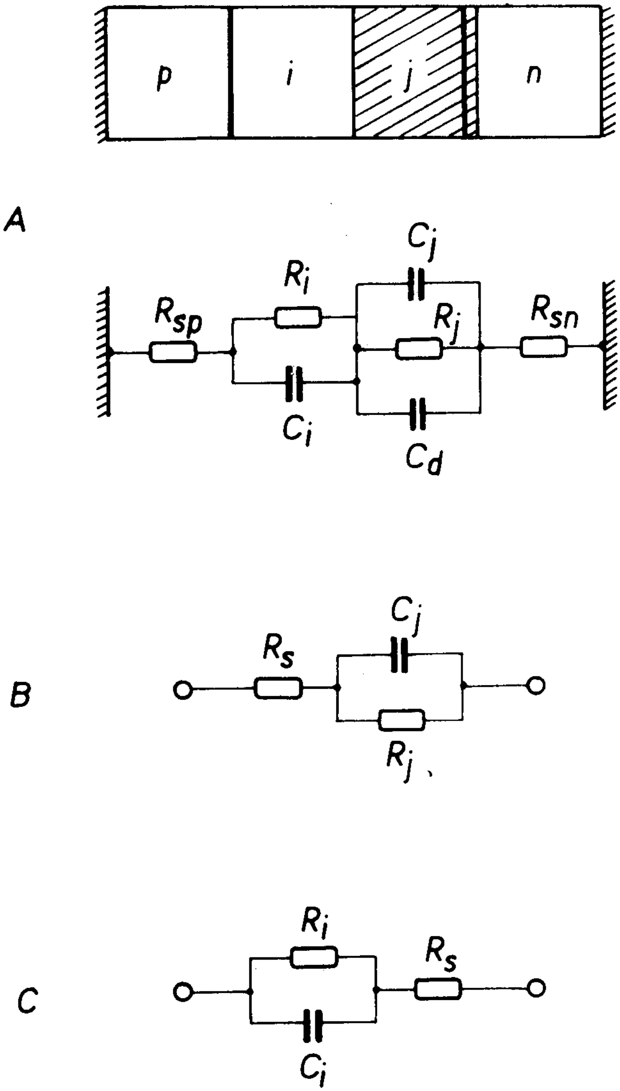

Fig.1. p-i-n diode structure and the equivalent circuit (A), backward bias simplified equivalent circuit (B), forward bias simplified equivalent circuit (C). $R_{sp}$, $R_{sn}$, $R_s$: resistances of the p and n - regions. $R_i$, $C_i$: resistance and capacitance of the i-region. $R_j$, $C_j$: resistance and capacitance of the exhaustion region. $C_d$: diffusion capacitance.

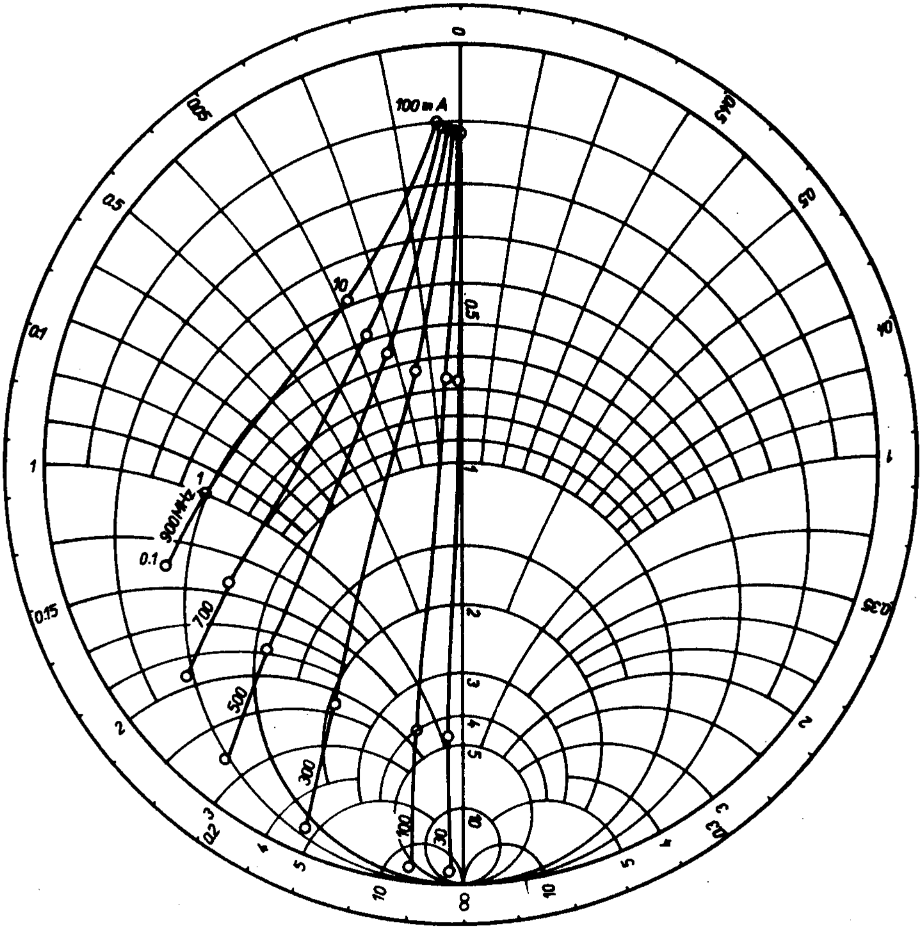

Fig.2. Small - signal impedance of the p-i-n diode twin. Chart center is 75 ohms.

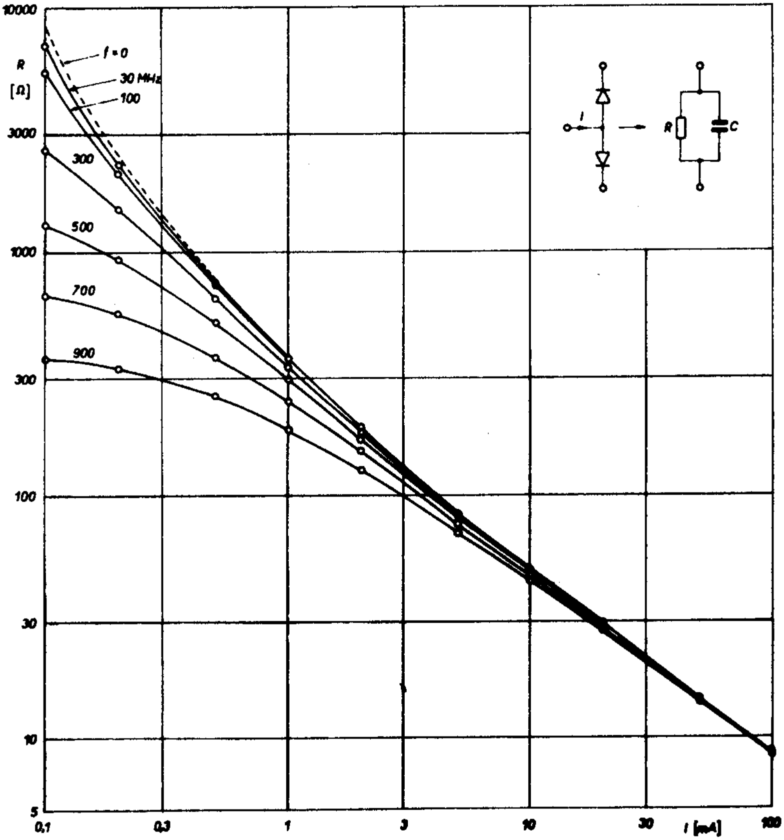

Fig.3. Resistance of the p-i-n diode twin.

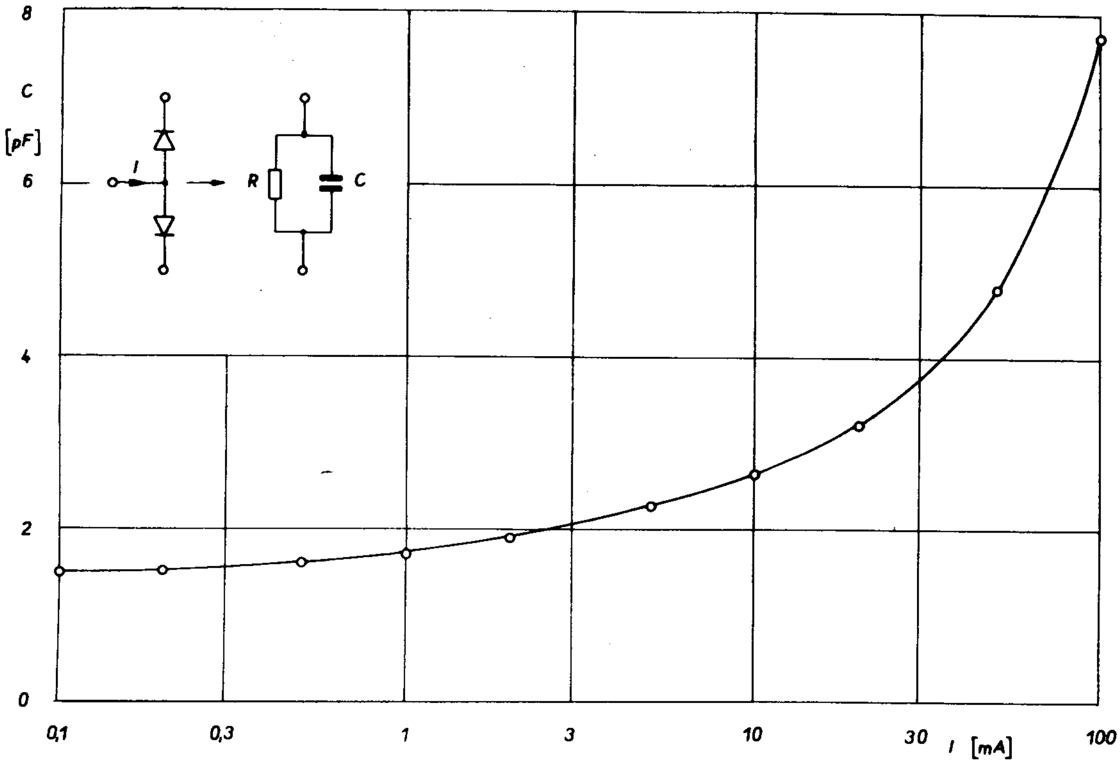

Fig. 4. Capacitance of the p-i-n diode twin.

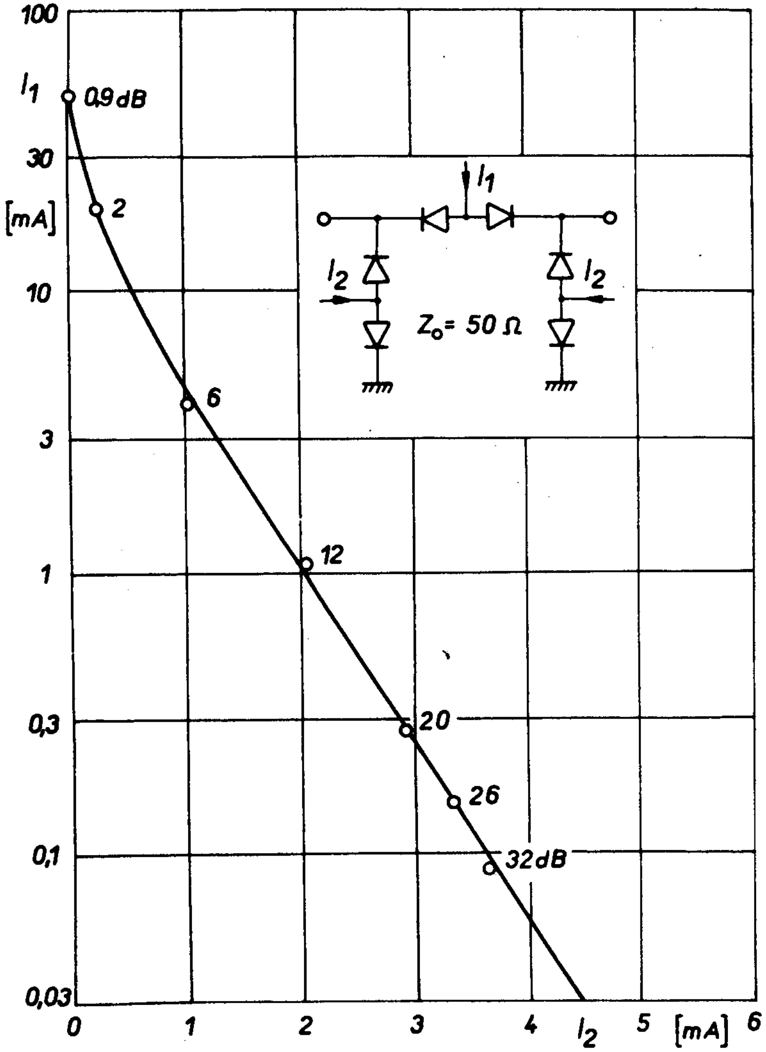

Fig.5. P - attenuator. The function of the currents $I_1$, $I_2$ and the attenuation for the constant characteristic impedance $Z_0$ = 50 ohms.

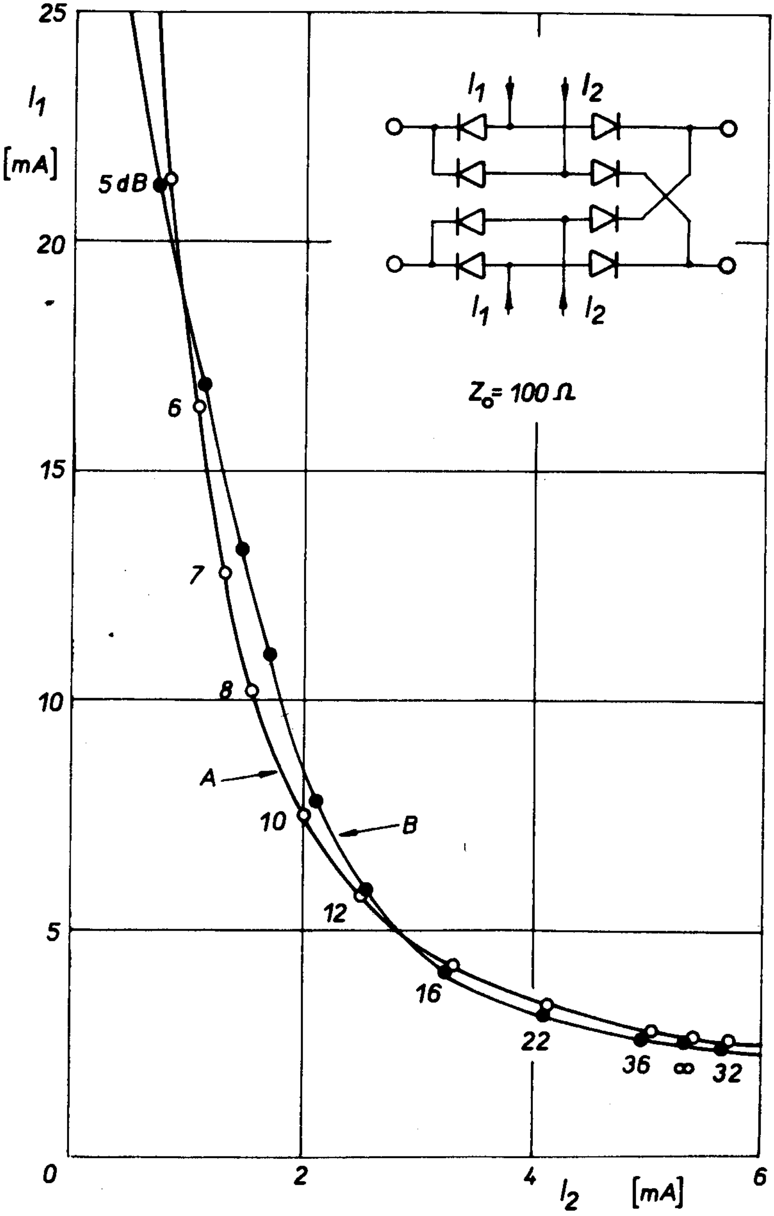

Fig.6. Bridge - attenuator. The function of the currents $I_1$, $I_1$ and the attenuation for the constant characteristic impedance $Z_0$=100 ohms.

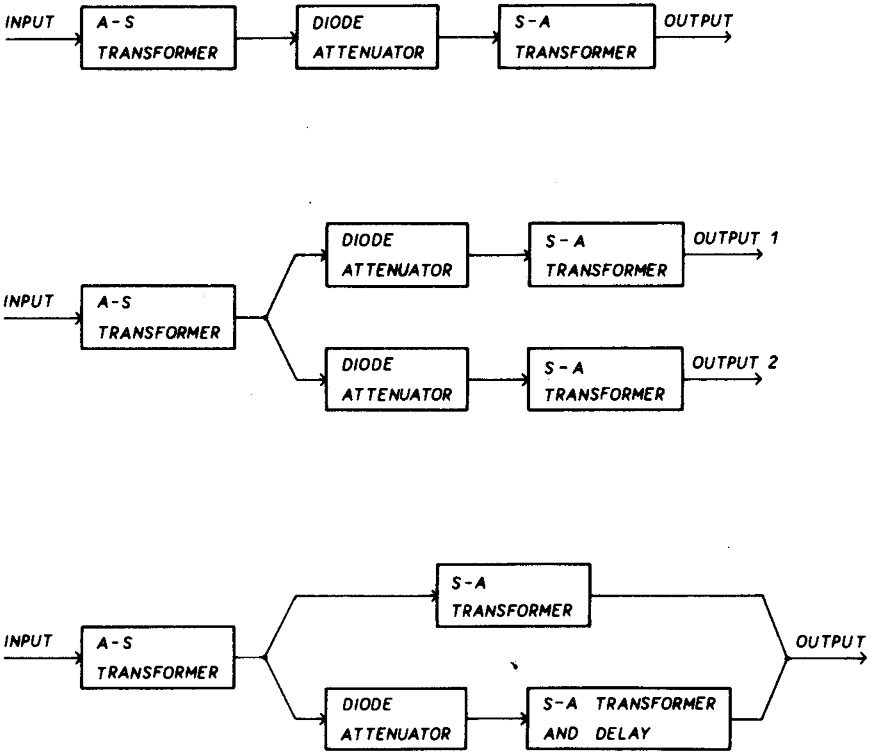

Fig.7. Block diagram of the diode attenuator - invertor (A), the diode attenuator bifurcation (B), the bipolar pulse shaper (C).

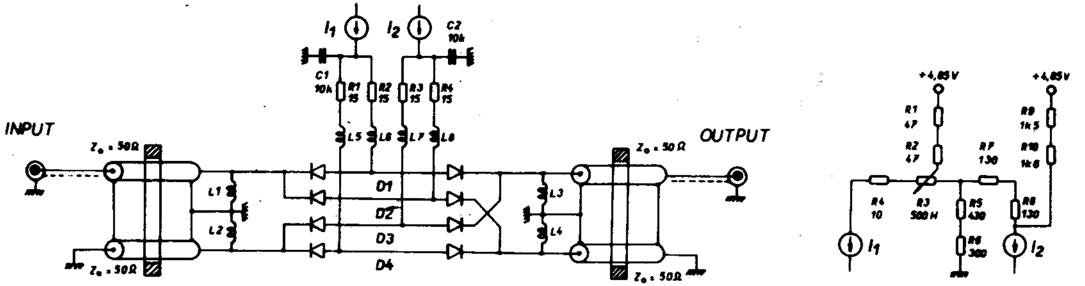

Fig.8. Diode attenuator - invertor and the control circuit for the continuous adjustment of the attenuation.

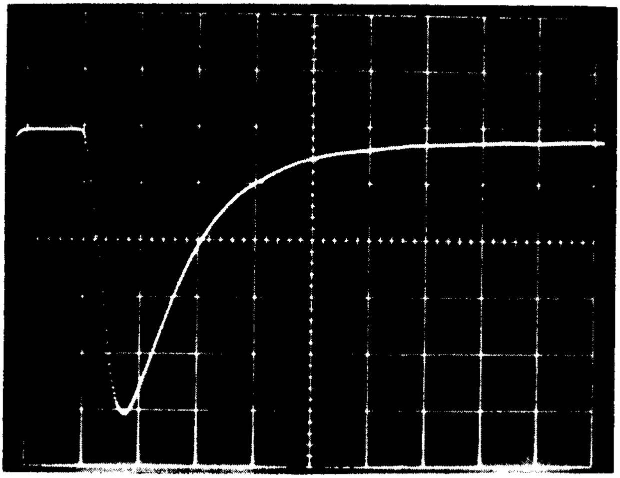

Fig.9. Input pulse to a diode attenuator. Scale 5ns/large division, 2 V/large division.

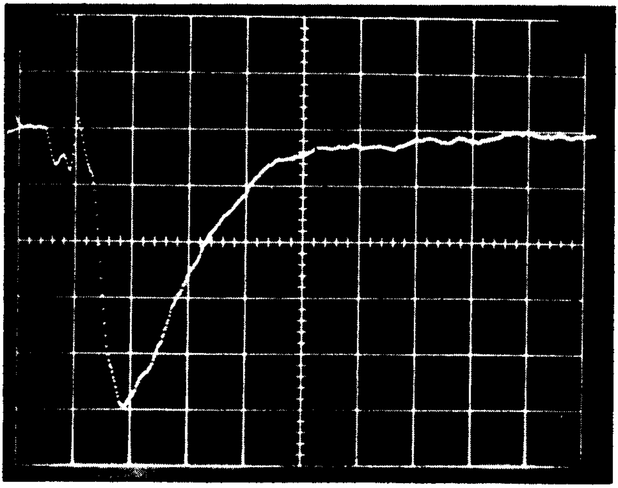

Fig.10. Output pulse from a diode attenuator. Attenuation: 40 dB. Scale 5 ns/large division, 20 mV/large division.