Variable Attenuator with Low Phase Shift

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Abstract — **A new base structure of the voltage-controlled phase invariant attenuator is described. This structure is based on T-attenuator with phase decoupling circuits. Design factors for decreasing the phase shift are discussed. A computer-aided design technique for minimizing phase shift in attenuator is presented. Measured attenuation of one section up to 15 dB is shown to be independent of frequency band up to 3 GHz. The adjusting parameters for one-stage attenuator were founded. Novelty of this paper consists in application of theorem of the minimum phase shift for the linear attenuator design.**

Index Terms — **Attenuator, low phase shift, phase invariance, diode structure, voltage control.**

I. INTRODUCTION

The paper describes the problems encountered to receive a minimum phase change versus attenuation voltage-controlled attenuator. Function of the phase invariant attenuator is to change the amplitude in the microwave signal processing with minimum impact on the phase characteristic. Variable phase invariant attenuator (VPIA) is required in system of automatic signal phasing in transmitters of the base station of mobile-communication system, automatic gain control, high-power amplifiers, measuring systems, etc [1]. VPIA is typically used in modern communication transceivers to automatically adjust RF signal levels to prevent saturation. In CDMA systems, a strictly power control led scheme can prevent near-far fading.

Two ways of reducing a phase shift are used in VPIA dependence on design. At first, it is a system of automatic phase shift compensation. At second, it is a device with some of the attenuation characteristics almost identical inclination on frequency in the working frequency band [2]. The first way essentially complicates a circuit, so the approach presented here utilizes the compensation of phase shift by adjusting circuits. A number of published works deal with the problem by using compensation techniques [2].

Novelty of this paper consists in application of theorem of phase shift minimum [3] for the linear T-attenuator with adjusting circuits and experimental researches for the VPIA design. Attenuator proposed in the given investigation is broadband vs attenuator described earlier, for example, in [4–5].

II. GENERAL CIRCUIT STRUCTURE

In the ideal variable attenuator the phase response should remain unchanged over its attenuation range. This property is particular importance in a growing number of wideband phase-sensitive signal processing applications. At microwaves, the phase performance of conventional attenuator designs is limited by inherent parasitics. The effect of the diode parasitic is to change the phase shift and group delay slightly away from that in the ideal case.

It is known that the exact invariance of phase shift in the controlled linear system at the attenuation adjusting is provided only when numerator *m* and denominator *n* of degrees for the polynomial transfer function are equal [3]. From the theory of linear circuits it is known that the condition *m=n* as a rule is reached in so-called crossed or bridged circuits with the mutual dependence the reactive elements. Therefore, it is necessary to join a crossed circuit with π or T-structure of controlled elements connection for attenuator designing. Hereon it is necessary to calculate parameters of adjusting elements.

Generally, VPIA is performed using a p-i-n diode controlled by the bias current, or GaAs MESFET in the electrical controlled resistance mode [1]. In this paper, p-i-n diodes are applied. Typically p-i-n diode is DC current controllable device and the attenuation level is dependent on the value of the p-i-n diode resistance, which is carried out by the forward bias current [6]. The attenuator bias circuit is very complex because of current source is difficulty for design. Also additional voltage-current converter is necessary. Consequently there is an increasing requirement for voltage-controlled attenuators [7].

In order to satisfy these requirements, a new VPIA and its control circuit are proposed. The attenuator consists of T-circuit of diodes and parallel resistor for matching. The proposed control circuit provides linear characteristics with range of specific input voltage.

III. CALCULATION OF ATTENUATION AND PHASE SHIFT

Analysis of VPIA was carried out on PC using the developed software [2-3]. The software operates in the analysis and optimization modes. The aim of optimization is the minimum phase shift at different levels of attenuation that corresponds to different levels of diode currents and consequently, their resistances. Calculation of

diode resistances has approximate character, as far as parameters of the volt-ampere characteristics of diodes and the dependences of their resistances from the current have a large disorder. In both modes of operation the program determines amplitude and phase characteristics of attenuator in a working frequency band at values of p-i-n diode resistance from minimum up to the maximum.

Analysis of VPIA we shall carry out with the linear circuit of a diode. For unpackaged diode the physical model presents itself parallel connection of controlled resistance (R_s, R_p) with capacity of transition (C). The effect of the parasitic within the diodes has been ignored. Typically at large values of R_s, R_p and frequencies below 10 GHz the parasitic junction capacitance becomes the dominant phase shifting.

Therefore model of attenuator looks like follows (see fig. 1). There $L1=L2=L$ is the correction inductance, R is parallel resistor for matching. In this T-circuit, series-connected p-i-n diodes operate as attenuators, while a shunt-connected diode operates not only as attenuator, and as a phase-shift compensation circuit. The T-network was used in order to obtain a combination of good insertion loss and attenuation range. Capacity of transition in a certain extent is possible to compensate by correcting circuits, that allows to realize a wide possible working frequency band and attenuation. The RLC-circuits usually use as correcting circuit.
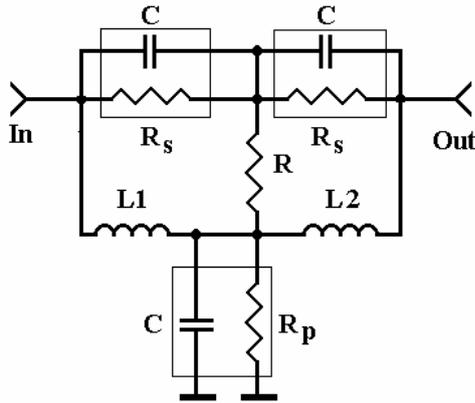

Fig. 1. The schematic diagram of the p-i-n diode attenuator

The Y-matrix of the attenuator is based on the equivalent circuit:

$$Y = \begin{bmatrix} 1/R_s + pC + \\ + 1/(pL) & 0 & -1/R_s - pC & -1/(pL) \\ 0 & \begin{matrix} 1/R_s + pC + \\ + 1/(pL) \end{matrix} & -1/R_s - pC & -1/(pL) \\ -1/R_s - pC & -1/R_s - pC & \begin{matrix} 2/R_s + 2pC + \\ + 1/R \end{matrix} & -1/R \\ -1/(pL) & -1/(pL) & -1/R & \begin{matrix} 1/R_p + 1/R + \\ + pC + 2/(pL) \end{matrix} \end{bmatrix}$$

It is easy to see that proposed bridge topology satisfies to conditions of the theorem on the phase shift minimum

[3]. Indeed, from Y-matrix of the attenuator follows that transfer factor has $m=n=3$ order – $(pC)^3$. However an analytical condition for the correcting inductances L vs. phase shift is difficult to receive because of the complexity transfer factor. It is more simply to find these parameters by optimization.

Typical capacity of the diode is about $C=0.2$ pF. Value of the matching resistance is $R=50$ Ohm. The optimum values for $L=0.19$ nH and optimal resistance of diodes has been founded (Table 1). The value of $R_{s,p\,max} = 1000$ Ohm was used for the desired attenuation of 15 dB approximately.

In Fig. 2 the electrical characteristics of attenuation are shown for the circuit without correction inductances and with ones. Fig. 3, 4 are the phase shift, defined as phase differences $\Delta\varphi_i=\varphi_i(f)-\varphi_0(f)$, $i=1...4$ for attenuations A_i. This design gave theoretically less than 0.160 maximum phase difference between 0.2 dB and 15.5 dB attenuation in a frequency band of 0.01–2 GHz on the software model. This exceeds previously reported results [6, 8]. In other attenuation range the phase shift changes much less. In the attenuator without $L1$, $L2$ the phase shift difference in same band reaches 57^0. Thereby, phase shift is reduced by correction more than in 100 times. The maximum attenuation is 15.6 dB. VSWR in full range of frequencies and attenuations is always less than 2.7.

TABLE I

ATTENUATION AND RESISTANCE OF DIODES

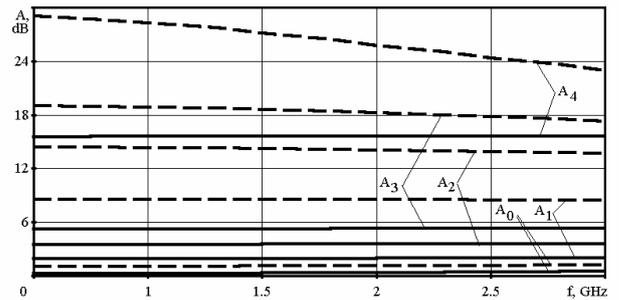| A	Attenuation with L1, L2, dB	Attenuation without L1,L2, dB	R_s	R_p
A_0	0.2–0.5	1–1.2	5	1000
A_1	1.9–2.0	8.5	50	100
A_2	3.5	14.4–13.7	100	50
A_3	5.2	19–17.3	150	30
A_4	15.5	29.3–23	300	5

Fig. 2. Attenuation characteristics vs. frequency in the circuit without (■ ■ ■ ■ ■ ■) correction and with (▬▬▬) correction
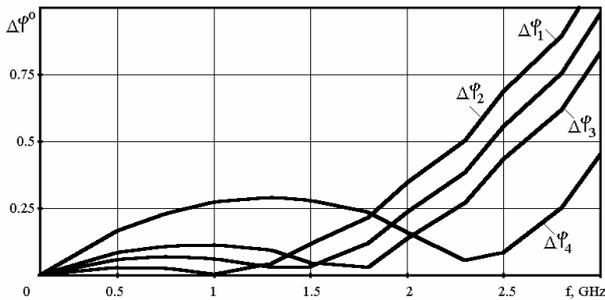
Fig. 3. Phase shift vs. frequency in the circuit
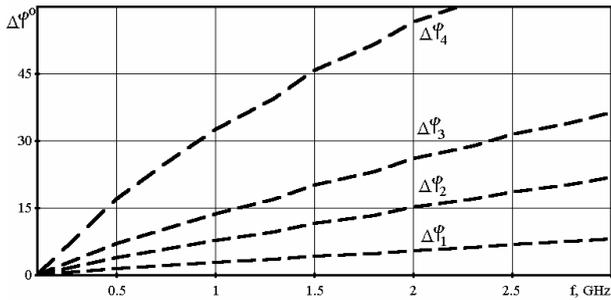with correction

Fig. 4. Phase shift vs. frequency in the circuit
without correction

IV. EXPERIMENT

The calculations above show better results than published with respect to the phase shift [5-8]. Therefore, to verify theoretical results and to gather experiences with regard to the feasibility of a practical system, an experimental attenuator in Fig. 5 was carried out and tested.
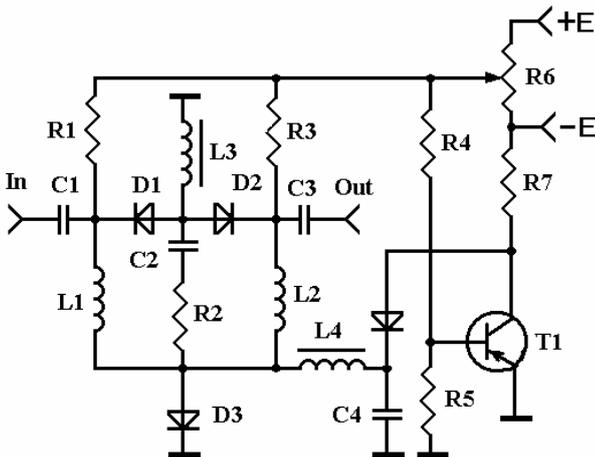

Fig. 5. VPIA experimental attenuator

The experimental VPIA is modified to accommodate the experimental convenience and availability. The aim of the design procedure is to obtain a large bandwidth of the attenuator response. A significant problem is caused by the mounting parasitics. This circuit was fabricated on a polycore layout with good dielectric properties. This package, with their electrically grounded base and short effective ground path lengths, produce excellent RF performance up to 3 GHz. Although the plastic packages are perfectly acceptable for today's GSM and telecommunication systems, they cannot support ultra-wideband applications.

To minimize adverse effects from biasing, the microwave part does not contain a bias network. Bias was applied to the p-i-n diode externally through the coaxial input. The biasing networks are located as far as possible from the direct signal paths.

All components are commercially available. As elements with controlled resistance, in this study the p-i-n diodes of 2A5117A have been used. It is a good analog of Hewlett-Packard's HSMP-4810 p-i-n diodes. The low frequency response is limited by the 75 pF DC blocking capacitors. In this design the series and shunt diodes are biased through resistors and inductances. A fixed supply of 12 V was used. A maximum current for the diodes was about 10 mA. The inductances $L1, L2$ provide phase stability, which combined with the diode's parasitic capacities and compensated for the phase shift variation when the attenuation is adjusted. Inductances may be fabricated as a transmission lines.

The operation of the attenuator can be explained as follows. When the movable contact of $R6$ bias is at its down position on the diagram, the diodes $D1, D2$ of the serial arm of the attenuator is open and have a minimum resistance. The diode $D3$ of the parallel arm is closed and has maximum resistance, and the transistor $T1$ is opened by a negative voltage on its base. In this case the attenuation is minimum (A_0). When the movable contact $R6$ is shifted to the upper position, the voltage at the cathodes of the diodes $D1$ and $D2$ is increased and the diodes begin to close. Increasing the control current will gradually forward bias the diodes, thereby decreasing their RF resistance. In order to provide attenuation with a minimum variation in phase, the diodes $D1, D2$ of the series arm should be closed more rapidly than the diode $D3$ open. This can be achieved using the transistor $T1$ provided addition negative voltage for $D3$.

The measured observations for the diode attenuator circuit have a good agreement with theoretical results described above. The minimum insertion loss was 0.5 dB. At operating frequency band up to 3 GHz the minimum phase shift was 3^0, where the maximum attenuation was 15 dB. This means the phase shift is 0.3 deg./dB attenuation, which is better than previously published results [5]. But as seen from Fig. 4, the phase shift increases rapidly if the attenuation exceeds 10 dB. Up to 18 dB attenuation, the phase shift is only 4.5^0. Higher attenuation can be obtain by multi-stages these attenuators using blocked capacitors between each stage and controlling the bias voltage simultaneously.

V. Discussion

Fig. 1 is a schematic diagram for computer-aided analysis and design. It is not an equivalent circuit of the actual circuit shown in Fig. 5. Due to availability and convenience, the actual circuit built and tested is close to the diagram but not exactly equal to it.

As elements with the controlled resistance the p-i-n diode was used, which parasitic reactive parameters provide the growing of attenuation with frequency increase, and consequently, to reduction of transfer factor. Therefore the phase shift cannot be reduced more than up to 2–5 degrees. Nevertheless, this way of phase shift stabilization is most wide-spread at present, because of simplicity attenuator design.

The presented computer-aided technique has shown that it is possible to reduce the phase shift to 0.3 deg./dB attenuation up to 18 dB at 2 GHz. This amount of phase shift is greater than waveguide attenuator but is smaller than previously published p-i-n diode attenuators [4-8].

VI. Conclusion

This paper describes the voltage-controlled phase invariant attenuator and the problems encountered and solutions devised to produce a minimum phase change versus attenuation. For example, T-attenuator has been theoretically and experimental observed and designed. It has been possible to overcome some disadvantages of the previous low phase-shift attenuator [4–8]. In the VPIA described above the change in transmission phase versus attenuation was reduced in 100 times through application of the invariance principle. The wideband attenuator is not limited to bandwidth that is more value for practice.

As seen from the presented example, an attenuator with an average of 0.3 deg./dB phase shift up to 2 GHz was constructed and modeled. The attenuator had similar phase shift up to 18 dB of attenuation across most of the band. Some theoretical analysis of the circuit has been performed.

Modern techniques demand a theory to developing a new VPIA at lower costs. The use of the correction circuits permits to achieve a more constant phase shift vs. attenuation and frequency by a sufficiently simple method. It permits to receive the actual achievable characteristics that open wide possibilities of improving the quality parameters of devices.

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