The Linear Theory and Engineering Design of the Phase Invariant Controlled Attenuator

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***Abstract* — On the base of the linear system theory a condition for minimum of the phase shift from attenuation in a voltage controlled attenuator (VCA) is founded. The base structure of the VCA is investigated. It is shown that fulfillment of the invariance condition provide a theoretically minimum of phase shift. For example, the paper disclosed details of the new attenuator design and discuss its performance. Its main difference from known consists in ultra broadband feature and large range of attenuation where minimum of the phase shift is reached at regulation. As a result of optimization, the correcting circuit parameters and adjusting parameters of diodes are founded.**

I. BACKGROUND

A voltage controlled attenuator (VCA) with the small dependence of phase shift at the attenuation regulation is used in microwave systems, where high phase stability is required. For example, it is system of automatic phasing of signals in transmitters, system of power summation in amplifiers, measuring systems etc [1]. VCA 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, which may increase the overall capacity.

In sub-surface radar the use of the phase invariant VCA is essentially necessary in multi-channel receivers of reflected signals, where signals from near and far distant zones are processed separately [2]. It is known that the exact invariance of phase shift in the controlled system is provided only when the amplitude-frequency characteristic (AFC) in the different attenuation state is constant in all frequency band [3]. It is unrealized in real devices, because of the working frequency band is always limited.

In VCA, in dependence on design, two ways of reducing a phase shift are used: designing a system of automatic phase shift compensations, or realization in the working frequency band some of the attenuation characteristics with an almost identical inclination on frequency. First way essentially complicates a circuit, so at present in the engineering practice the compensation of phase shift by correcting circuits is widely used.

***Novelty** of this paper consists in determination of conditions of minimum phase shift at the regulation of attenuation for the linear attenuator with correcting circuits.*

As elements with the controlled resistance a diode and transistor are widely used, which parasitic reactance 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.

II. REDUCTION OF PHASE SHIFT BY CORRECTING CIRCUITS

The possibility of broadband VCA development is defined by reactive parameters of controlled elements. Their values should be small and constant during regulation. In this connection the improvement of qualitative parameters of attenuator is connected with improvement of controlled elements and their effective using. The most spreading elements are FETs and diodes with small parasitic parameters, in particular, p-i-n diodes.

Modern p-i-n diodes practically has not inductive impedance. 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. Another way of compensation consists in creation of the second channel of signal transfer with delay, compensating delay of signal in the first channel. In the paper the theory and application of the first way is considered.

III. THE NECESSARY CONDITION OF THE PHASE SHIFT MINIMUM

We shall consider a complex transfer factor for the linear system:

$$K(j\omega)=\frac{\sum_{i=0}^{m} a_i\,(j\omega)^i}{\sum_{i=0}^{n} b_i\,(j\omega)^i}=\frac{C(j\omega)}{Z(j\omega)}=$$

$$=\frac{\operatorname{Re}C(\omega)+j\operatorname{Im}C(\omega)}{\operatorname{Re}Z(\omega)+j\operatorname{Im}Z(\omega)}$$

where $C(j\omega)$, $Z(j\omega)$ are some numerator and denominator polynomials. Phase-frequency characteristics (PFC) is determined as:

$$\varphi(\omega) = arctg\,\mathrm{Im}\,C(\omega)/\mathrm{Re}\,C(\omega) - \\ - arctg\,\mathrm{Im}\,Z(\omega)/\mathrm{Re}\,Z(\omega).$$

Let us consider PFC in two states for a circuit: *i*-th, which is determined in the mode of minimum attenuation and *j*-th, under which attenuator introduces some attenuation in a tract. Then phase shift, determined as a difference between PFC in these states, for the phase invariant attenuator must be the least:

$$\Delta\varphi(\omega) = \varphi_i(\omega) - \varphi_j(\omega) \to \min.$$

But

$$\begin{aligned}\Delta\varphi(\omega) &= arctg\,\mathrm{Im}\,C_i(\omega)/\mathrm{Re}\,C_i(\omega) - \\ &- arctg\,\mathrm{Im}\,Z_i(\omega)/\mathrm{Re}\,Z_i(\omega) - \\ &- arctg\,\mathrm{Im}\,C_j(\omega)/\mathrm{Re}\,C_j(\omega) + \\ &+ arctg\,\mathrm{Im}\,Z_j(\omega)/\mathrm{Re}\,Z_j(\omega) = \\ &= \varphi_1(\omega) + \varphi_2(\omega)\end{aligned} \quad (1)$$

By grouping separately differences of arctg(.) for numerator and denominator polynomial, we have received two artificial PFC $\varphi_1(\omega)$ and $\varphi_2(\omega)$. A new transfer factor for $\varphi_1(\omega)$ is following:

$$K_1(j\omega) = \frac{\mathrm{Re}\,C_i(\omega) + j\,\mathrm{Im}\,C_i(\omega)}{\mathrm{Re}\,C_j(\omega) + j\,\mathrm{Im}\,C_j(\omega)} = \frac{C_i(j\omega)}{C_j(j\omega)},$$

and for $\varphi_2(\omega)$ similarly is:

$$K_2(j\omega) = \frac{\mathrm{Re}\,Z_j(\omega) + j\,\mathrm{Im}\,Z_j(\omega)}{\mathrm{Re}\,Z_i(\omega) + j\,\mathrm{Im}\,Z_i(\omega)} = \frac{Z_j(j\omega)}{Z_i(j\omega)}.$$

It is easy to see that phase shift in two attenuation states will be least from all possible one, if

$$C_i(j\omega) = C_j(j\omega), Z_j(j\omega) = Z_i(j\omega).$$

It is possible to achieve, equating polynomials or separate factors *a* and *b* transmission functions in different states. Thereby it is possible to determine parameters of correcting circuits at given values of parameters of controlled elements. On the other hand, from (1) it is follows that for the minimum of phase shift under certain minimum $arctg\,\mathrm{Im}\,C_i/\mathrm{Re}\,C_i$, it is advisable to $arctg\,\mathrm{Im}\,Z_j/\mathrm{Re}\,Z_j$ was the least. It means that at given m it is necessary to reduce n. But from condition of the physical realizing it is follows that always $m \le n$. Consequently, it is necessary at least once $m=n$. This condition is not sufficient: if parameters of correcting circuits during regulation of attenuation are constant, it is impossible to receive $C_i=C_j$ strict equality or $Z_i=Z_j$.

IV. OPTIMIZATION OF THE ATTENUATOR PARAMETERS

The high order of transfer function of the modern circuits does a computed impossible the direct using of previous item results on equating polynomials. In the engineering practice the design of attenuators is connected with the optimization of the correcting circuits parameters. However the same level of attenuation can be received by different values of controlled elements. Thus the phase shift also will be different. Hence, it is necessary two enclosed cycles for optimization - separately for controlled elements and for correcting circuits.

V. THE PHASE INVARIANT ATTENUATOR CIRCUIT

The base structure of the VCA experimental model with one p-i-n diode in serial arm and two in parallel [4] with correcting a phase shift considered in this study, is shown in Fig. 1. This circuit was fabricated on a polycore layout. The high-frequency part of the circuit represented as a thin-film hybrid integrated module and is assembled on the substrate with good dielectric properties.

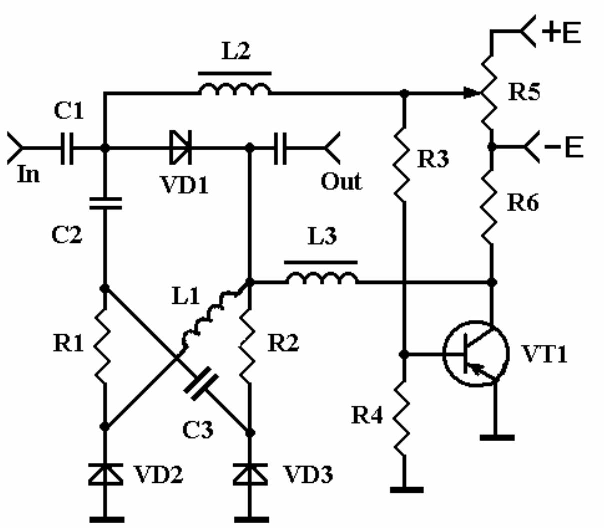

Fig. 1. Attenuator circuit

Phase stability is provided the inductance L1 and capacity C3, which combined with the diode's parasitic capacities and compensate for the phase shift variation when the attenuation is adjusted. The attenuator operates as follows. When the movable contact of R5 is at its upper position on the diagram, the diode VD1 of the serial arm of the attenuator is open and have a minimum resistance. The diodes VD2 and VD3 of the parallel arm are closed and have maximum resistance, and the transistor VT1 is closed by a positive voltage on its base. In this case the attenuation is minimum. When the movable contact R5 is shifted to the down, the voltage at the cathodes of the diodes VD2 and VD3 is decreased and the diodes are open. In order to increase the attenuation with a minimum variation in phase, the diode VD1 of the series arm should be closed more rapidly than the diodes VD2 and VD3. This can be achieved using the transistor VT1.

Analysis of VCA we shall carry out with use of the linear circuit of a diode. For unpackaged diode it flowing resistance and inductances are very small. So physical equivalent circuit presents itself parallel connection of controlled resistance with capacity of transition. Therefore equivalent of attenuator looks as follows (see fig. 2).

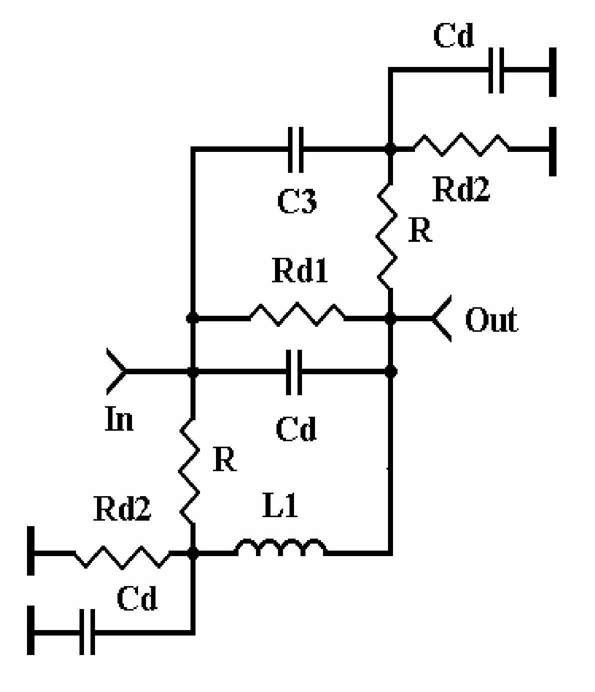

Fig. 2. The attenuator equivalent linear circuit

It is easy to see that topology satisfies to conditions of the theorem on the phase shift minimum (see above). Transfer factor has m=n=4 order (in the circuit it is four independent reactivities). Equating coefficients at $(j\omega)^3$, it is possible to receive the following condition of phase invariance: $Cd \cong C3$. It is impossible to receive an analytical condition for the correcting inductance L1, because of the complexity factor is very difficulty. It is more simply to find this parameter by optimization.

R VD1	R VD2, VD3	Attenuation in the circuit with correction	Attenuation in the circuit without correction
5	1000	0.8	0.8
25	250	3	3.5
50	75	6	7.5
120	40	9	12
200	20	12	17.5
250	15	14	20
500	5	20	26

TABLE I

Diode resistances

All components are commercially available. As elements with controlled resistance, the p-i-n diodes of *2A517A* have been used. Capacity of the diode is about *C=0,2* pF. Values of the matching resistances *R1=R2=50* Ohm. Optimization of diode resistances gives following values (see Table1).

The optimum parameters of correcting circuits were founded: L1=0.8 nH, C3=0.3 pF. It has allowed to achieve the following frequency characteristics. On fig. 3 and 4 the characteristics of attenuation for the circuit without correction and with correction accordingly, and on fig. 5 and 6 – PFC are shown.

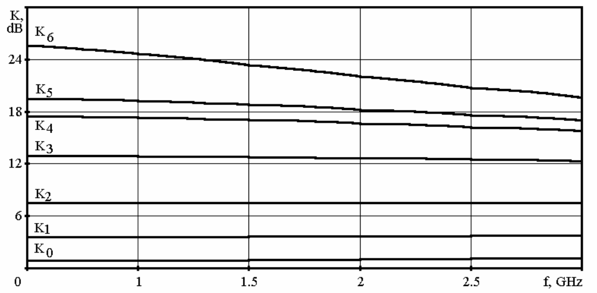

Fig. 3. Attenuation characteristics as function of frequency in the circuit without correction

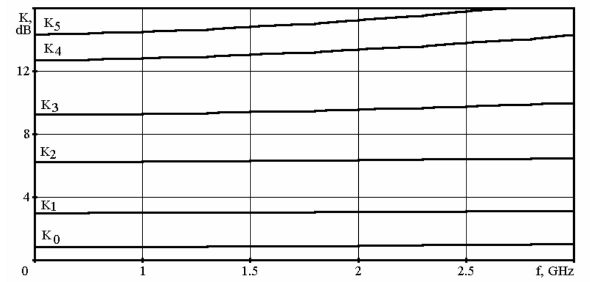

Fig. 4. Attenuation characteristics as function of frequency in the circuit with correction

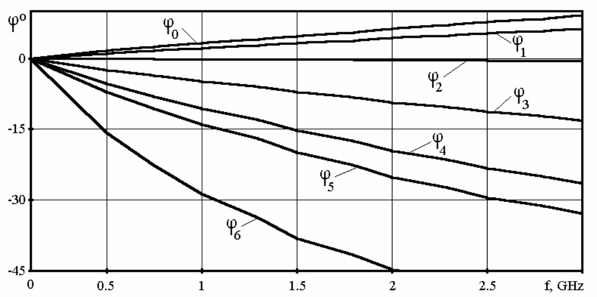

Fig. 5. Phase characteristics as function of frequency in the circuit without correction

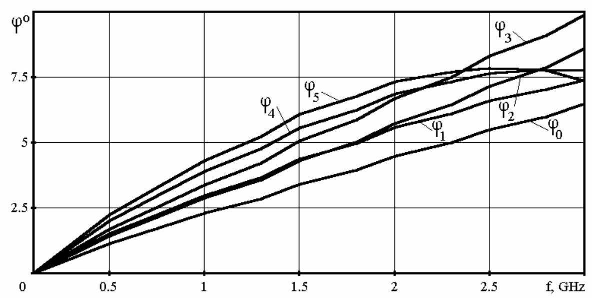

Fig. 6. Phase characteristics as function of frequency in the circuit with correction

VI. DISCUSSION

Figures 4, 6 show that the maximum phase shift variation within the attenuation range up to 20 dB does not exceed 2 degrees in a frequency band of 0.1–2 GHz. In another attenuation ranges the phase shift is more less. In the attenuator without L1, C3 the phase shift in same band reaches 50 degrees (see Fig. 5). Thereby, phase shift is reduced to the account of correction almost in 25 times. The maximum attenuation is 26 dB, the VSWR in full range of frequencies and attenuations is always less than 1,5.

For the comparison, we will show the PFC of circuits, in which capacity C3 is replaced on the inductance L2. In this case, obviously, the phase shift compensation will also takes place from the appeared second channel of signal transfer from input to output (R-L1 and R-L2). The signal delay from the capacitive nature of the diode resistance will be compensated by the inductive resistance of the second channel. However, degrees of numerator and denominator polynomials of the transfer factor are not equal (m=3, n=4). Consequently, necessary condition of the phase shift minimum is not carried out. Optimization of parameters L1 and L2 was carried out at the same parameters of diodes, as for the circuit with adjusting circuits L1, C3. In result, the following values of the correction inductances were founded: L1=0.15 nH, L2=0.04 nH. From fig. 7 it is seen that maximum value of the phase shift variation in the circuit in the attenuation range up to 20 dB does not exceed 8 deg. in the frequency band of 0,1-2 GHz. This is four as large than in the previous circuit.

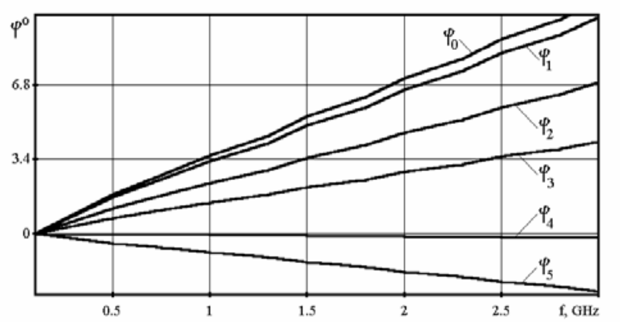

Fig. 7. Phase characteristics as function of frequency in the circuit with inductive correction

In both cases the phase error can be explained by the large parasitic capacity of diodes. To decrease the phase error, a further study in evaluating of the diode capacities is necessary. As a rule, the phase stability has only been reached in the attenuation range smaller than in 1,5-2 times of maximum attenuation. For increase the attenuation level, the attenuators can be cascaded and the resulting phase shifts remain reasonably stable [5].

VII. CONCLUSION

The function of the phase invariant attenuator is to change the amplitude in the processing of microwave signal with minimal impact to the phase characteristic.

This paper describes the phase invariant attenuator and the problems encountered and solutions devised to produce a minimum phase change versus attenuation for an impedance-matched electronically variable attenuator. The low phase shift attenuator is shown to overcome some disadvantages of the existing phase shift attenuator. In the paper it is shown what conditions must satisfy a transfer function. Also we define a possible ways for use this condition at the engineering design of attenuator. An example of VCA have been considered, which is designed using received theoretical results.

Modern techniques demand a theory to developing a new generation of components at lower costs. The use of the correction circuits permits to achieve a more constant phase shift via regulation of the transfer factor by a sufficiently simple method. It permits to receive the potential achievable characteristics, that open wide possibilities of improving the quality parameters of devices.

REFERENCES

[1] RF Digital Attenuators in Plastic MLP Packages. In *Microwave Journal*, October 2000, vol. 43, No. 10. P. 166-176.

[2] O.V. Stoukatch, L.P. Ligthart, "P-i-n Diode Attenuator with Small Phase Shift for Ultra-Wideband Pulse Subsurface Geo-Radar". In *32 European Microwave Week*. 2002, 23-27 September. Milan, pp. 1065-1067.

[3] O.V. Stoukatch, "Theory and Design of the Experimental Super-Broadband Digital Attenuator". In the *Proceedings of the European Microwave Week*, 2003, 6-10 October, ICM, Munich, Germany. London, Horizon House Publications, pp. 281-283.

[4] S. Walker, "A Low Phase Shift Attenuator", *IEEE Transactions on Microwave Theory and Techniques*, vol. 42, no. 2, p. 182, February 1994.

[5] Won-Tae Kang, Ik-Soo Chang, Min-Soo Kang, "Reflection-Type Low-Phase-Shift Attenuator", *IEEE Transactions on Microwave Theory and Techniques*, Vol. 46, No. 7, pp. 1019-1021, July 1998.