Theory and Design of the Experimental Super-Broadband Digital Attenuator

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***Abstract* – A new theoretical results and experimental model of the super-broadband code voltage-controlled attenuator with low phase shift is considered. It is proven that phase invariance achieved if ratio of pulse responses maximum in two different states is constant. With the improvement in the microwave performance, the control circuit provides the absolute accuracy for the overall device. The results shown that performance of the attenuator with correcting circuits and the code voltage-control is better than the transmission-type phase shift attenuator with the same measurement specifications.**

I. BACKGROUND

Modern modulation techniques will require theory to demand a new generation of components with high quality features. They will require improved performance at lower expenditures. The phase invariant code-controllable attenuators provide this capability.

In multi-channel systems aimed for power addition in microwave amplifiers, antenna arrays, signal auto-phasing, controlling capacity level, etc. the independence of the phase shift response concerning effect in connection to the control of the signal amplitudes is required [1].

Super-broadband digital attenuators have been used to set power levels in RF and microwave circuits for many years. It is to electronically switch resistive T- and π-networks to attenuate and control signals. Herewith attenuators must have low insertion loss, generate attenuation levels, maintain low input and output VSWR for all attenuation levels, and switch very quickly.

II. THEORY

A super-broadband signal is composed of both amplitude and phase elements, but the phase characteristics can be distorted with the variance of attenuation due to the several problems. As we observe in paper [2], the phase characteristic is variable with the varying attenuation because of the diode resistance characteristics.

The theory of attenuator operation is that input signal is divided into two equal signals with each processed through a variable attenuator and then combined at the output. As a result, each signal, one increased from the 0^0 phase state and one increased from the 180^0 phase state, will cancel the errors of each other and remain constant in phase and amplitude variations vs. frequency while changing attenuation values. In effect, it is two arms of attenuators that perform a task while providing compensations to improve the overall performance.

We shall find conditions of invariance phase-frequency characteristic (PFC) to amplitude-frequency characteristic (AFC) in attenuator with variable states. Let us consider ratio of complex transmission characteristics in *n* and *n+1* states

$$\begin{aligned} &K_{n+1}(\omega)\exp(j\varphi_{n+1}(\omega))\,/\,K_n(\omega)\exp(j\varphi_n(\omega)) = \\ &= K_{n+1}(\omega)\,/\,K_n(\omega)\exp(j\Delta\varphi(\omega)) = \\ &= M(\omega)\exp(j\Delta\varphi(\omega)), \end{aligned} \qquad (1)$$

where

$$\Delta\varphi(\omega) = \varphi_{n+1}(\omega) - \varphi_n(\omega)\,, \qquad (2)$$

$K(\omega)$ and $\varphi(\omega)$ are AFC and PFC accordingly, ω is angular frequency. At $\Delta\varphi(\omega)=0$ the ratio of AFC modules can be in general case frequency dependence value. Function $M(\omega)$ must be the constant frequency dependence value, as $M(\omega)$ changes an order of transfer function. It is possible to shown by considering of transfer function $K(j\omega)$ in a kind of fraction-rational function. According to (1), changing a system state from *n* to *n+1* requires multiplying the transfer function by $M(\omega)$. However order of transfer function does not need to change. Obviously, it is possible only if

$$K_{n+1}(j\omega)\,/\,K_n(j\omega) = M\,. \qquad (3)$$

Minimum difference between maximums of the pulse characteristics is enough for optimization of phase invariant systems. Indeed, this follows from theorem about maximum [3]:

$$\begin{aligned} &\sup_{t>0} x(t) = \lim_{m\to\infty} \sup_{j\omega>0} (-1)^m (j\omega)^{m+1} [K(j\omega)\,/ \\ &/(j\omega)]^{(m)} / m!\,, \quad m = 1,2,... \end{aligned} \qquad (4)$$

With regard to (3) we shall receive for *n* and *n+1* states

$$\sup x_{n+1}(t) / \sup x_n(t) = M\,.$$

Thus, a necessary and sufficient condition for invariance PFC to AFC is constant ration of absolute maximums of the transitive or pulse characteristics. Basing of received ratio it is possible to define invariance property without calculation of PFC. Conditions of invariance allow to optimize attenuator in time domain.

III. CIRCUIT

For attenuator designing the extensive modeling was performed to minimize insertion loss, and phase shift, and optimize the attenuation flatness by the individual bits.

During this process it was determined that optimal digital control is very important to attenuator accuracy, and must be optimized to minimize sensitivity to external loading and bit errors.

Figure 1 shows the experimental model of the *p-i-n* diode attenuator. In this 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.

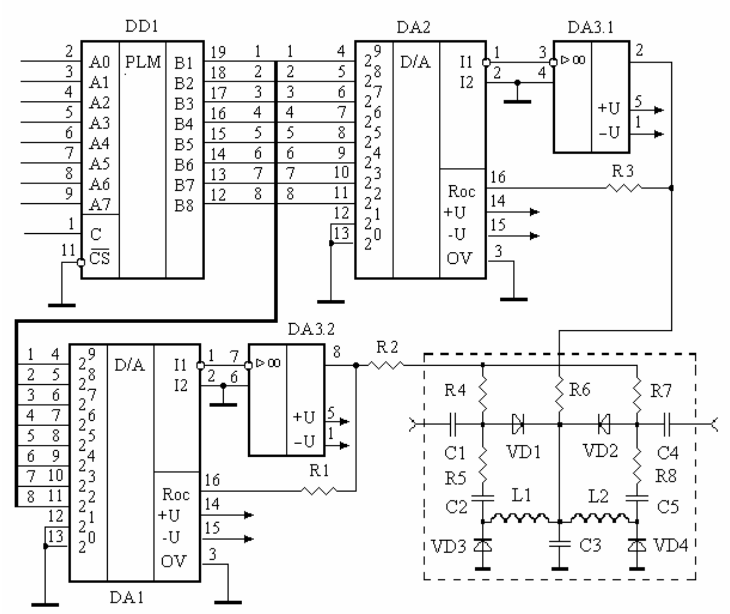

Figure 1. Attenuator circuit

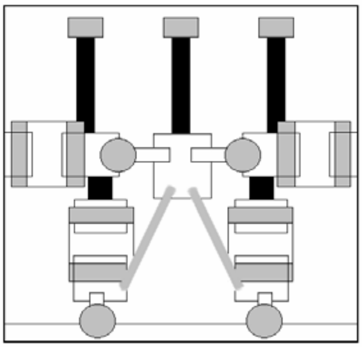

Figure 2. Attenuator layout

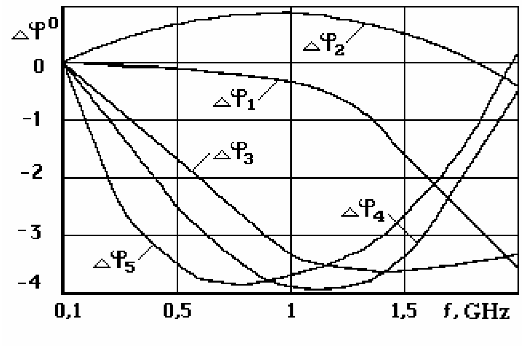

Figure 3. Phase shift vs. frequency

P-i-n diodes of 2A517A as elements with controllable resistance have been used. Inductance and capacity of the diodes are *L=0,1 nH, C=0,3 pF*, respectively. The choice of a diode was an important design consideration. In a high frequency super-broadband application, the inductance and capacity of diode leads adversely affects the attenuation and phase. This diode installed using a proprietary technique reduces the series inductance and provides a significant improvement in performance.

Circuit was fabricated on a ceramic layout as shown in Figure 2. Ceramic packages, with their electrically grounded base and short effective ground path lengths, produce excellent RF performance up to 3 GHz. Recent developments in MMICs technologies have expanded operating frequencies while reducing physical size and costs. Although the plastic packages are perfectly acceptable for today's GSM and PCS telecommunication systems, they cannot support tomorrow's higher frequency applications.

Control circuit and MMIC are attached to the ground with epoxy. To minimize adverse effects from biasing, the biasing networks are located as far as possible from the direct signal paths.

Phase stability provide the inductance *L1*, *L2* and capacity *C1*. Combined with the diode's parasitic parameters, they form a low-pass filter and thus compensate for the phase shift variation when the attenuation is adjusted.

The optimal diode control during continuous adjustments of attenuation allows typical performance achieved phase frequency characteristics as shown in Figure 3.

The phase shift, defined as phase differences $\Delta\varphi_i(f)=\varphi_i(f)-\varphi_0(\omega)$, i=1,2,…5 was achieved for different attenuations within the range 1.5...24 dB and in frequency band 0.1...2 GHz. Figure 3 shows that the maximum phase shift variation within the attenuation range up to 24 dB does not exceed 5 degrees in a frequency band of 0.1...1 GHz. The maximum attenuation is 40 dB, the VSWR is always less than 2.2 in full frequency band and attenuations range.

As simple attenuators, used as components for control circuit blocks, the output current of the attenuation controller must be small and the dynamic range of the attenuator is comparatively small. However, the phase shift is very stable. Cascading multiple phase invariant attenuators improves phase and amplitude characteristics, as well as increases dynamic attenuation range.

Typical switching speed is 15 ns with rise and fall times of three ns. Logic inputs are TTL compatible. A logic 0 sets the bits to reference loss while a logic 1 selects the attenuation levels.

The 8-bit digital model has 256 steps. The optimal performance values are stored in the EEP-ROM ready to be commanded from the digital control (do not shown in figure 1). With the improvement in the microwave performance, it is the control circuitry that provides the absolute accuracy for the overall device.

IV. 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 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.

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 simple method. It permits to coming the potential achievable characteristics.

REFERENCES

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