

# Microwave delay lines for analogue signal correlation

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## ABSTRACT

Noise radars use random or pseudo-random signals to illuminate a target and coherent detection techniques in order to process received noise signals. In the range of microwave frequencies the simple analogue systems of the correlative detector may be used. It helps to overcome the fact that the real digital implementation of the autocorrelation function for these frequencies is very difficult. A correlator receiver is a typical element of the noise radar. The important issue is that coherent reception needs delay lines of constant or variable parameters to be applied in the receiving systems. To address this issue the paper comprises comparison of available technologies of microwave analogue delay lines. The advantages and disadvantages of presented solutions are presented. The paper comprises: the types of basic delay unit technologies, tunable and controlled-delay lines.

**Keywords:** delay line; analogue correlation; noise radar

## 1. INTRODUCTION

Delay lines with ability to tune the physical or electric length are used in a number of applications in the field of microwave engineering. The most interesting application seems to be a reference signal delay in noise radars [1-4]. The principle of noise radar technology and applications, especially to determine a target distance and radial velocity are presented in a number of papers [5-10]. Although the full digital receivers are under the interest [11-13] detection of target movement, especially micro-movement (e.g. breathing and heart rate for vital signs detection) can be done with the use of analogue signal correlator. In order to perform the coherent reception of a transmitted signal a noise radar receiving system needs delay lines of constant or variable parameters.

To address this issue the paper comprises comparison of available technologies of microwave analogue delay lines. The advantages and disadvantages of presented solutions are described. It is assumed that the scope of the interest is frequency range for delay lines equal to form 1 to 10 GHz and working bandwidth is equal to 1 GHz. A digitally-controlled line with switched reference sections is introduced. Next, a microwave analogue tapped delay line is presented.

As far as radar is concerned, the time delay of transmitted signal should be regarded as round-trip length and real radar range is half a distance corresponding to full delay. For example, when radar to target distance is 50 meters the round-trip signal path is equal to 100 meters and whole propagation time delay (round-trip) equals about 333.33 ns.

Therefore, for radar range equal to 50 m the delay line in signal processing block should be set to value of delay equal to 333.33 ns. This delay line may be implemented in various technology therefore its physical length does not need to be equal to 100 m.

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## 2. DELAY LINE CLASSIFICATION

Delay lines may be divided into various groups depending on design requirements. As far as tunability is concerned the classification is as follows:

- fixed delay lines (fixed length),
- tuned delay lines (tuned physical or electrical length).

The lines with changeable length by means of electronic tuning may be divided with respect to the type of driving into two groups:

- analogue tuning, in the meaning of continuous in time tuning,
- digital tuning, in the meaning of stepped or multi-state in time tuning.

The digitally-tunable lines may be divided into following sub-groups:

- switched length,
- reflective.

Further, complex delay lines configurations with respect to availability of delay states may be described as:

- one time delay value available for one configuration (switched lines),
- all time delay states available simultaneously (tapped lines).

The digitally-tunable delay line allows a number of pre-defined values of time delay to be set. When the electrical length of the line is tuned by analogue means there is no pre-defined steps and the length may be tuned in a continuous way.

## 3. FIXED DELAY LINES

### 3.1 TEM transmission lines

The most natural way to obtain desired value of time delay is the use of a section of TEM transmission line. The most popular way is the use of dielectric-filled coaxial line. However, for respectively higher time delays the coax lines present relatively big dimensions and weight. The signal attenuation also increases, especially for higher frequencies. The physical implementation of coaxial delay lines commonly appears in a form of big coils made from thin coaxial transmission line, usually semi-rigid cable. Commercially available solutions have typical working frequency range and bandwidth 0÷6 GHz, available delay 1÷250 ns, but at the cost of insertion losses from 0.2 to 50 dB [14].

### 3.2 Planar structures

In order to obtain smaller overall dimensions transmission delay lines may be realized in the form of planar structures made on dielectric substrate with high permittivity. The most common structure is a section of microstrip or coplanar line. On the other hand, there are additional ways to obtain higher values of propagation delay based on using various planar structures, and they are as follows:

- meander lines [15-19], especially multi-layered with interlayer connections by via holes (3-D meander) [20,21]
- interdigital structures [22]
- spiral lines
- coupled lines in the form of microwave bandpass filter optimized for flat group delay in required frequency band

The multilayer planar delay lines are commonly realized in LTCC (Low Temperature Co-fired Ceramics) technology. The available parameters are: bandwidth 1GHz at carrier frequency about 10 GHz, insertion loss lower than 1 dB, time delay up to several ns.

### 3.3 Delay lines with acoustic waves

The use of acoustic surface waves techniques (SAW) assumes conversion of electrical signal to mechanical wave, which propagates in the form of material vibration along its surface. The device that uses this technique consists of input electrical-to-mechanical transducer, a specially prepared layer of piezoelectric material and inversely operating mechanical-to-electrical transducer at the output. The propagation velocity of acoustic wave is thus much lower than for electromagnetic waves because of the fact that the acoustic wave travels at velocities of 3000 to 12000 m/s. The SAW devices allow obtaining delays from few nanoseconds to several hundred nanoseconds with frequency bandwidth up to 800 MHz. Their main disadvantages are the increased insertion losses that can reach values more than 25 dB and the frequency limitation to about 2.5 GHz. It should be pointed out that these devices are not tunable [23].

Another, similar technology is bulk acoustic wave (BAW) that uses mechanical waves excited to propagate through whole volume of prepared material. This allows realizing greater delays compared to SAW devices, ranging from few hundreds of nanoseconds to several thousand microseconds [24].

BAW technology overcomes the frequency limitation of SAW one (2.5 GHz) and allows reaching frequencies of about 20 GHz and a frequency bandwidth up to 2 GHz. Similarly to SAW technology, the insertion losses are high, more than 30 dB, and depend on the realized time delay and the operating frequency. The examples of commercially available BAW device parameters are:  $f_0=1\text{GHz}$ ,  $B=0.5\text{GHz}$ ,  $\tau=4 \mu\text{s}$ ,  $\text{IL} = 47 \text{ dB}$  and  $f_0=10\text{GHz}$ ,  $B=2 \text{ GHz}$ ,  $\tau=0.5 \mu\text{s}$ ,  $\text{IL} = 50 \text{ dB}$ .

## 4. TUNABLE DELAY LINES

### 4.1 Transmission lines periodically-loaded with varactor diodes

In some applications, a transmission line may be substituted with the set of cascaded lumped inductances and capacitances in the form of multistage lowpass filter. This lumped elements corresponds to distributed unit inductance and capacitance of the transmission line. A transmission line in the meaning of delay line may be realized in this technology. Typically used number of stages ranges from a dozen to several tens and depends on assumed group delay values.

Propagation of microwave signal (with respect to parameters not field pattern) along such a structure is similar to propagation in transmission line as far as the signal wavelength is long compared to elements dimensions.

This, so called, artificial transmission line, may be additionally loaded by periodically placed varactor diodes, connected in parallel to lumped capacitances [25] – Figure 1.

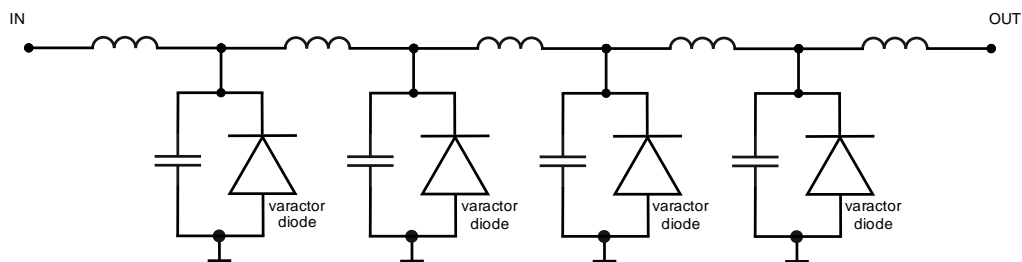


Figure 1. Schematic of artificial transmission line with periodically connected varactors

The design and structure of the whole line is optimized in order to obtain the possibility of changing the propagation constant (thus group delay) in line by applying bias voltage to varactor diodes thereby causing the change of equivalent artificial line shunt capacitance.

Another solution is the use of planar transmission line e.g. coplanar line, which is loaded at regular spacing by a series of varactor diodes, that serve as voltage dependent shunt capacitors (Figure 2).

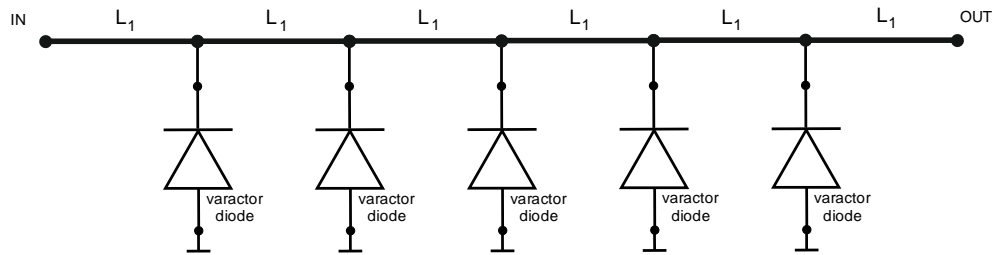


Figure 2. Schematic of a nonlinear transmission line (NLTL) with periodically connected varactors

This type of lines is also called nonlinear transmission line (NLTL).

Artificial transmission lines, are lowpass filters i.e. they exhibit an upper limit of frequency band. In order to obtain bigger values of time delay higher values of unit capacitance and inductance are needed and it lowers maximum frequency of propagating signal.

Additional disadvantages of such a line are:

- change of varactor capacitance (in order to change delay) causes a change of line characteristic impedance and therefore input and output impedance matching,
- necessity of precise and reproducible driving of bias voltages,
- nonlinear distortions of propagated signal introduced by nonlinear characteristics of varactor diodes.

This distortions are higher for higher delay values due to varactor bias near to zero volts.

#### 4.2 Fiber optic delay lines

Microwave delay lines may be realized with the use of optical techniques. Most commonly used solution is the conversion of electric signal to intensity modulated light signal and then transmission through an optical fiber. At the output an optical receiver converts modulated optical power back to electric signal. The time delay is introduced during the propagation along the optical fiber. The value of time delay is proportional to the fiber length. Propagation velocity of the optical signal inside the fiber is lower than speed of light in vacuum and single-mode optical fiber overall diameter is about several tenth of millimeter. Therefore it is possible to obtain large time delay using enough long optical fiber rolled with relatively small overall external dimensions [26].

The input circuit of optical delay line comprises a light source i.e. laser with direct-modulation or CW laser with external modulator e.g. Mach-Zehnder device. At the output an optical receiver in the form of PIN photodiode is commonly used with optional electric signal amplifier.

To sum up, the microwave optical delay line is a kind of analogue microwave optical link with appropriately assorted length of the optical fiber. It exhibits advantages and disadvantages inherent to optical techniques.

Advantages:

- possibility to obtain large delay time, from several ps to hundreds of  $\mu$ s, dependent on the optical fiber length,
- low signal losses, for optical fiber less than 1dB/km,
- overall dimensions of rolled optical fiber are much smaller compared to adequate length of coaxial microwave transmission line,
- frequency range up to dozen of GHz.

Disadvantages:

- necessity of use specialized components as: power supply, laser, modulator, photodiode and amplifier,

- in spite of low loss of optical fiber the overall insertion losses of the whole optical link (including efficiency of optical modulator and photodiode) are from 20 to 40 dB. The use of high laser power and external modulator allows lowering the insertion losses at the cost of complexity and power consumption.
- photodiode generates additional noise signal resulting from optical signal noise and detection process,
- because of fact that light modulation (direct and external) and detection are nonlinear processes the whole optical link introduces nonlinear distortions.

The optical delay lines has possibility of tuning the delay value [27]. This feature may be obtained with the use of laser source with tunable wavelength and optical fiber with high dependence of group velocity versus light wavelength.

The example of commercially available optical delay line parameters is:  $B=0.05 \div 13$  GHz,  $\tau=500$  ns,  $IL = 39\text{dB}@1\text{GHz}$ .

#### 4.3 Reflective varactor-controlled load

In some applications a precision phase shifter with group delay control is needed. The control range is usually small and equal to about a half of the wave period. The structure consists of one 3dB quadrature coupler (0 and 90 deg of output phase shift) and two varactor diodes with driving circuits [28]. An outline of such a circuit is shown in Figure 3.

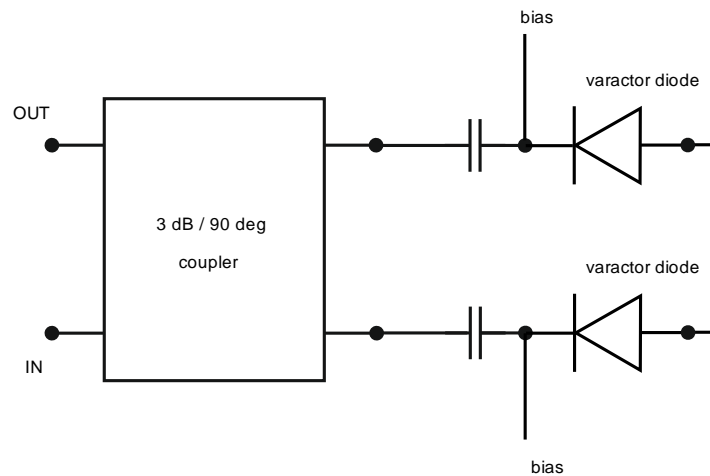


Figure 3. Schematic of reflective phase shifter with adjustable load.

The hybrid coupler may be designed with the use of distributed elements i.e. transmission lines or lumped elements as LC structure with specially optimized values.

Disadvantages:

- limited frequency bandwidth of the coupler,
- non-uniform coupler's response in frequency,
- small values of time delay,
- coupler's insertion losses,
- overall circuit insertion losses dependent on varactor bias voltage (that means circuit phase shift).

Advantages:

- good impedance matching to external network resulting from the use of 3dB quadrature coupler,
- possibility of precise adjustment of phase shift value.

## 5. CONFIGURATIONS OF MICROWAVE DELAY LINES WITH CONTROLLED DELAY

### 5.1 Cascaded line with switched delay sections

Cascaded line with switched delay sections consists of  $N$  stages where  $N$  is the number of bits. Each stage refers to one bit and comprises two SPDT switches and two sections of delay line, the first is a reference line  $\tau_0$  ("zero delay"), the second is a line with assorted basic time delay  $\tau_n$  [29-30]. The subsequent stages contain basic time delays that fulfil the rule:

$$\tau_n(n) = \tau_1 2^{n-1} \quad (1)$$

where  $n$  is the number of the bit, and  $\tau_1$  is the time delay difference between states (or in other words delay at lowest state). For example, for  $N = 3$  bits the basic time delays equal  $\tau_1$ ,  $2\tau_1$ , and  $4\tau_1$  (Figure 4).

The delay lines: the references and the basics may be connected between each other by means of synchronically operated SPDT switches. The overall number of available delay values (and states) is  $2N$ , and the obtained time delay is between  $N\tau_0$  (the first state) and  $(2N-1)\tau_1$  (the last state). General scheme of digitally-controlled delay line with switched delay sections, for  $N=3$ , is shown in Fig. 3. Assuming that the value of basic time delay  $\tau_n$  contains the amount of reference delay  $\tau_0$ , the first state introduces the time delay equal to  $N\tau_0$  and the last state  $(2N-1)\tau_1 + N\tau_0$ . Hence, the time delay difference with respect to the reference path is from 0 to  $(2N-1)\tau_1$ .

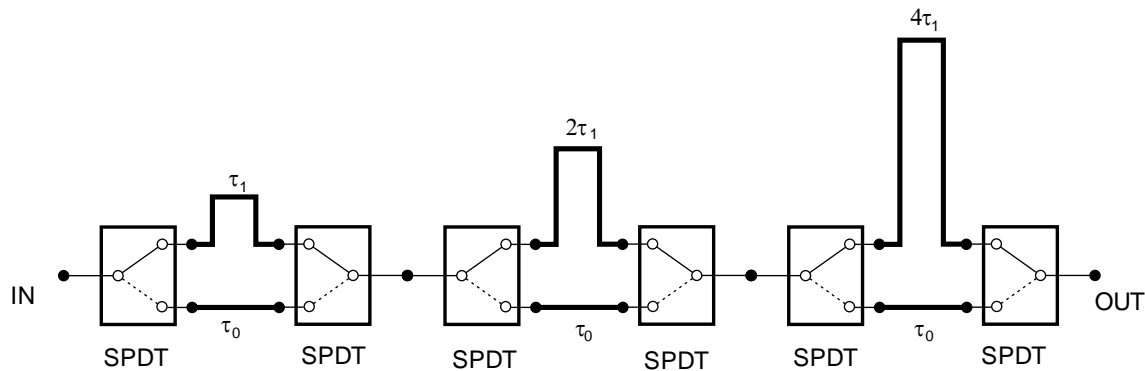


Figure 4. General scheme of digitally-controlled delay line with switched delay sections, example for number  $N$  of bits equal to 3.

There is a number of advantages and disadvantages related to digitally-controlled delay lines. For cascaded line with switched delay sections they are as follows.

Disadvantages:

- insertion losses of used SPDT switches and their additive accumulation due to cascading,
- necessity of use of  $2N$  switches for  $N$  bits of control,
- potential existence of transient-state during simultaneous driving of switches,
- influence of non-flat switch response within the frequency band (i.e.  $S_{11}$  and  $S_{21}$ ),
- existence of non-zero reference delay resulting from non-zero length of connections in reference path,
- there is only one value of time delay available at the time of switched-on state, that results from principle of operation.

Advantages:

- for number  $N$  of stages there is  $2N$  available states i.e. time delay values.

## 5.2 Trombone line

The another solution of digitally-controlled delay line is a line with digitally-added basic delay sections called the trombone line [31,32]. In this solution there is no reference sections, the line consists of two pathways of cascaded basic delay line sections, each of them having the same value of delay equal to half of the lowest state delay  $0.5\tau_1$ . Each pathway is a microwave two-port network, it comprises an input/output port and the second port is connected to matched load. There is a tap in point between every cascaded two basic lines and corresponding taps placed on two pathways are connected by means of SPST switch, usually realized as a pair of transistors in cascode connection. The number of basic delay sections per pathway equals required number of delay states. The SPST switches are normally-open, the onset of a chosen device causes to switch-on a delay patch of corresponding length i.e. value of time delay. Once a switch is activated the whole structure of delay line starts conducting a microwave signal between the input and output ports.

General scheme of trombone delay line with added delay sections is shown in Figure 5.

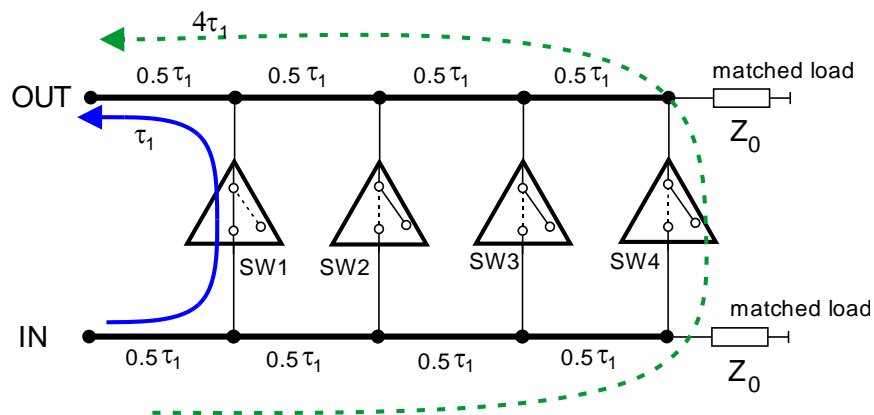


Figure 5. General scheme of digitally-controlled delay line with digitally-added basic delay sections (trombone line).

As far as the trombone line is concerned, there is no additive accumulation of insertion losses of the switches. In this line there is only one switch in conducting state during the state of delay. However, there are additional power losses due to signal absorption in matched loads ending the signal pathways. Physical structure of the line results that for  $N$  available delay states there are  $N$  basic delay stages required.

Both types of digitally-controlled delay lines mentioned above require properly designed basic delay units i.e. having insertion and return losses as low as possible. The basic delay lines may be realized in any kind of technology as far as the requirements indicated above are fulfilled.

## 5.3 Reflection-type line with switched delay sections

The delay line structure may be constructed with the use of reflective sections of transmission line [33]. The reflective scheme means that one end of a section of transmission line is short-circuited and the second end serves as input and output of delayed signal. In order to separate the input and output signals a microwave circulator is used. An outline of such a circuit is shown in Figure 6.

The short-circuited section of a transmission line serves as a unit delay element. In order to obtain switching of this value a SPST switch is used, which in open state allows signal to enter the delay section and in close state provides the short-circuit at the input of delay section. The microwave circulator may be replaced by a microwave coupler (3 dB 90 deg), as it is shown in Figure 7.

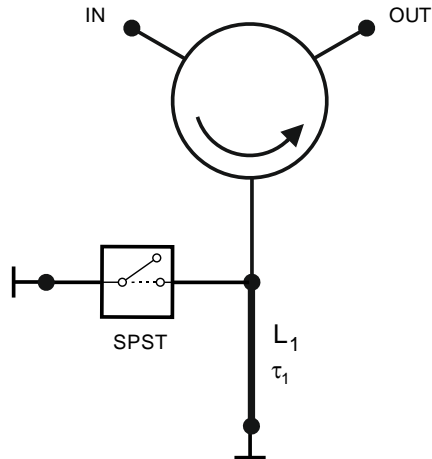


Figure 6. General scheme of one stage reflective delay line with microwave circulator.

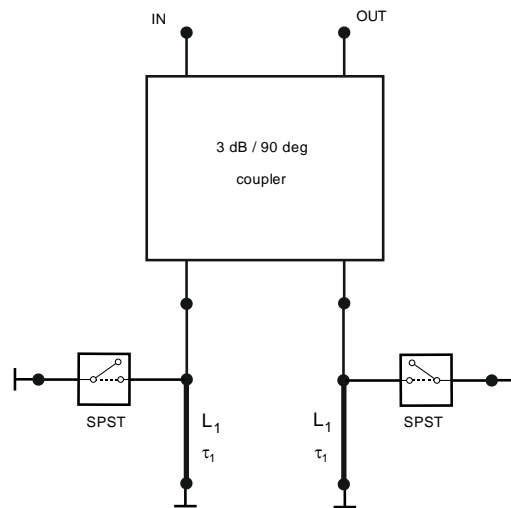


Figure 7. General scheme of one stage reflective delay line with microwave 3dB quadrature coupler.

The following scheme may be multiplied to obtain multi-state solution. This situation is shown in Figure 8.

Disadvantages:

- limited frequency bandwidth of the circulator or coupler,
- non-uniform circulator's or coupler's response in frequency,
- circulator's or coupler's insertion losses,
- short-circuit is realized with accuracy limited by the (signal losses) resistance of SPST switch,
- doubled number of delay sections in case of coupler compared to scheme with circulator.

Advantages:

- small length of delay sections, a short-circuited line delays signal two times more with respect to its length.



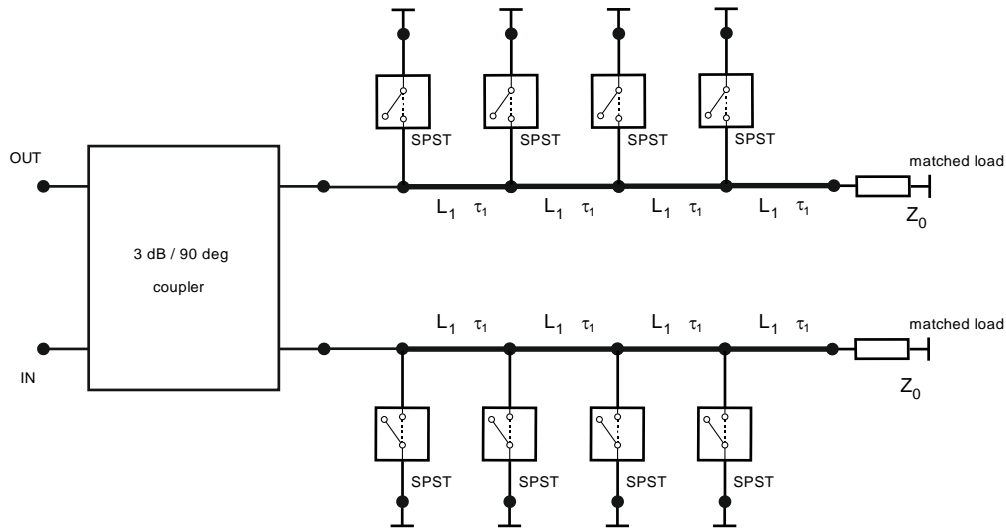


Figure 8. General scheme of one stage reflective delay line with microwave 3dB quadrature coupler.

#### 5.4 Analogue tapped cascaded delay line

In order to have a number of analogue correlations simultaneously another special kind of delay line may be used. This is the analogue tapped delay line.

The analogue tapped delay line consists of a number unit delay sections and microwave couplers connected in a cascading way (Figure 9 [34]). The couplers have the same coupling factor. One delay line stage consists of one unit delay line with one coupler. The output ports for subsequently delayed signals are based on coupled signal ports. The time delay for every stage is equal to the number of the stage multiplied by the unit time delay  $\tau_1$ . General scheme of analogue tapped delay line is shown in Figure 9.

Every signal tap may be regarded as one time gate and may be connected to one signal correlator.

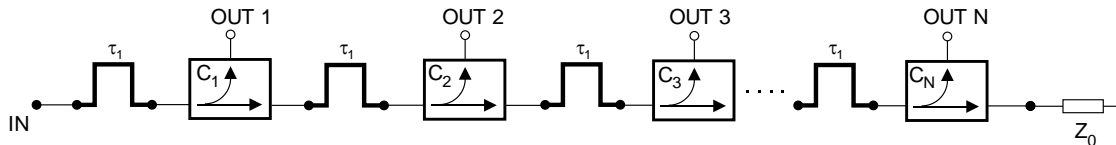


Figure 9. General scheme of analogue tapped cascaded delay line.

The analogue tapped delay line allows obtaining all time-gate signals almost simultaneously, as the signal propagates down the cascaded structure. However, in this case a signal switch (SPDT or SPST) implemented to set the one desired value of time delay is not needed.

The analogue tapped cascaded delay line offers several advantages:

- multiple values of time delay quasi-simultaneously,
- absence of unstable or transient states,
- absence of microwave switches and their insertion losses,
- absence of driving and bias signals.

To compare, there are disadvantages:

- necessity to provide high signal isolation between taps to minimize crosstalk,
- maximal number of delay gates depends on the signal coupling factor at each tap,
- insertion losses of microwave couplers.

Another way to design the analogue tapped delay line is the optimization of microwave coupler's coupling factor in order to obtain the same signal power at each tap.

## 6. DISCUSSION

There are several technologies for implementation of microwave delay line, both commercially available and in state of development.

Delay lines in BAW technology offer high insertion losses it means that the switched delay line set using these lines will have very high signal losses. This fact practically excludes BAW lines as complex digitally-controlled lines component. In this case the insertion losses of microwave switches are far less than BAW lines insertion losses. Moreover, switching the subsequent states in digitally-controlled line toward higher time delay causes in this case the stepped increase of whole delay path insertion losses. This effect is not avoidable even though the trombone structure is used.

The sections of TEM lines used as the unit delay components offer low insertion losses and the time delay is proportional to the physical length of the line. It means that to obtain high value of time delay the adequately long line is required. When the delay line is realized in coaxial technology the whole delay lines set may occupy quite big volume.

The use of planar technology, especially with substrates of high permittivity, allows to shorten physical dimensions of delay lines. TEM or quasi-TEM planar lines may be in that case substantially shorter, however when semiconductor substrates are used (MMIC) high signal losses may occur.

Further decrease of unit delay element dimensions is possible by means of the use of special planar structures, for example 2D and 3D meander lines or distributed interdigital capacitance lines in LTCC technology. The delaying structures in the form of band-pass filters based on coupled planar lines allows obtaining compact dimensions and relatively high group delays, however at the cost of frequency band. The group delay is approximately constant for a frequency range lower than the pass band. Closely to the edges of pass band the group delay strongly depends on frequency.

Comparison of existing delay line technologies allows concluding that in spite of constant development there is no ideal solution still. It is extremely difficult to combine the features like: low losses, high delay, low cost and small dimensions in one delay line design or technology.

The choice of solution to implement a delay line in a real system depends on the project requirements. There is a way to combine components available on the market with specialized solutions designed on demand. In the case of noise radar with analogue correlator one may consider the combined solution including a set of switched and tapped delay lines. The technique of analogue correlation is especially useful in a case of noise radar when the center frequency of transmitted signal bandwidth equals about a dozen of GHz. For such a case there is extremely difficult to apply direct technique of analogue-to-digital conversion.

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