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Evolutionary Trends in True Time Delay Line Technologies for Timed Array Radars

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ABSTRACT

Timed array technology is rapidly evolving in multiple areas such as high resolution imaging radar, automotive, medical, high data rate communication applications etc. Timed arrays by utilising True Time Delay (TTD) lines in place of phase shifters mitigate beam squint and pulse dispersion issues associated with wide instantaneous bandwidth arrays. This paper presents on review of evolutionary trends in TTD line architectures starting from coaxial cable to photonic integrated circuit. The paper also reports on critical parameters of TTD lines, their importance and implication in design of typical X-band imaging radar. Comparison of different TTD line architectures in terms of configuration, implementation, merits and demerits are discussed in detail for wideband array application. The paper also brings out the integration aspects of TTD lines as part of T/R modules and proposes suitable design schemes towards performance optimization and realisation of timed arrays.

Keywords: True time delay; Timed array; MMIC; T/R modules; Photonic integrated circuit; UWB; Phased array; RFSOC; FPGA

1. INTRODUCTION

Over the past few decades, radar technology is rapidly evolving from mechanical to passive phased arrays to active phased arrays and at present to Digital arrays. The phased array radars with multi-function capabilities are widely used in target detection, tracking, imaging, and high precession weapon delivery applications. However, conventional phased array radars for ultra-high-resolution imaging applications employing narrow-band phase shifters for electronic steering suffer from beam squint and pulse dispersion[1-3]. The beam squint is a diverging beam direction for different microwave frequencies at increased steering angles from the center frequency. The beam squint plot for X-band phased array radar with 2 GHz bandwidth at 20° scan angle is shown in Fig. 1. If the beam squint is more than the antenna beamwidth results in image distortion in terms of contrast and spatial resolution. The pulse dispersion in wide bandwidth arrays is due to the difference in time of the signal arriving at each of the antenna elements at different scan angles. When these signals are summed, they will combine coherently in phase but not in time resulting in poor image resolution in case of phased arrays. The above two issues associated with wide instantaneous bandwidth radars are mitigated by replacing narrow-band phase shifters with TTD lines. TTD lines with time response independent of frequency make it useful for wideband applications.

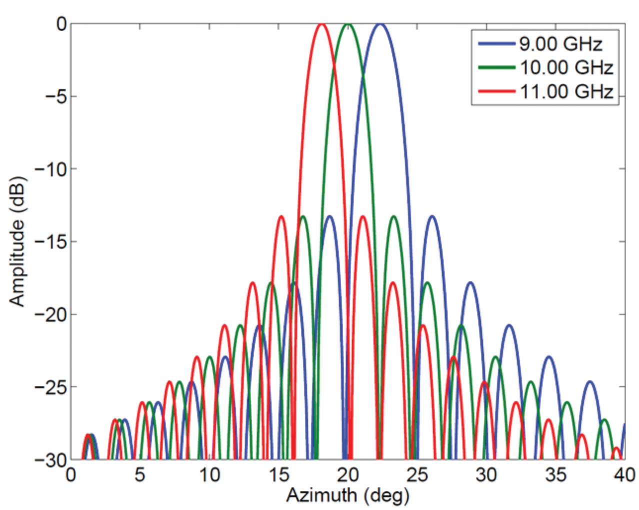

Figure 1. X-band phased array beam squint @ 20° scan angle.

The TTD lines are bulky and expensive compared to the phase shifters, making it very difficult to use in large size timed array systems. TTD line being a critical component of timed array, this paper presents on review of its evolutionary trends starting from analog type Rotman lens, coaxial cable type to modern MMIC and PIC type for timed array applications. Planar transmission line viz., microstrip/stripline/Coplanar Wave Guide based TTD lines in multi layer configuration of reduced size are reported in[12-13]. MMIC based TTD lines of 4 to 6bits up to 20 GHz wide bandwidth, delay of <500ps based on GaAs and RF CMOS technologies are reported in[15-17]. Optical delay lines based on optical cables, dispersive fibers, ring resonators, fiber bragg gratings, Silicon Photonic Integrated Circuit of nano to micro second delay are reported in[19-22]. Digital delay lines based on Field Programmable Gate Arrays (FPGA), RFSOCs, direct sampling RF ADC/DACs, Application Specific Integrated Circuits (ASIC) etc., meeting

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both finer resolutions in pico seconds to longer delay in seconds for DBF arrays reported in[26].

The paper also presents on performance comparison of different TTD line technologies such as coaxial, switched planar, MMIC, Optical, digital delay line types towards improvement in size, weight, cost and performance of timed array systems. The paper also discusses on critical parameters of TTD lines and their impact on performance of typical X-band imaging radar in detail. The paper brings out the integration aspects of TTD lines as part of T/R modules and proposes suitable design schemes towards performance optimization and realisation of timed arrays.

The paper is organized into six sections. Concepts of timed arrays and TTD lines are described in sections 2 and section 3. In section 4, types of TTD lines are discussed, and their performance comparison is presented in section 5. The paper concludes with a summary and references in section 6.

2. TIMED ARRAYS

The timed array utilizes differential time delay between the array elements for beam steering to overcome the beam squint and pulse dispersion effects of phase steered arrays associated with Ultra Wide Band (UWB) applications. Timed arrays are widely used in different high bandwidth data rate applications viz., automotive, medical, remote sensing, radars, EW, and communication systems[4]. The tactical Intelligence, Surveillance, and Recognizance (ISR) systems used in highly accurate target location and identification require Synthetic Aperture Radars (SAR) for imaging with ultra-high resolution of the order of 10 cm[5]. These radars are generally long range radars operating in either X or ku band with a wide instantaneous bandwidth of 1GHz and above. The instantaneous bandwidth (B) of radar is inversely proportional to radar range resolution which depends on compression pulse width (τ_p) in µsec as

$$\tau_p = \frac{\text{Range resolution in meters}}{150} \tag{1}$$

and $B = 1.2/\tau_p$ (2)

For example imaging radar with 15 cm range resolution corresponds to compressed width (τ_p) of 1ns and equivalent to instantaneous bandwidth of 1.2 GHz. Phased array radars commonly used for tracking and detection application using phase shifters will work well for a narrow RF bandwidth in per cent of center frequency up to twice the 3 dB array beam width in degrees[6]. In X-band (10 GHz center frequency) phased array radar with 1 deg antenna beamwidth, the maximum permissible instantaneous bandwidth will be 400 MHz, corresponding to an image resolution of 45 cm for distortion less performance. However, for better resolution, wider bandwidth is required, hence performance degradation is expected. In addition, the UWB radars with wider scan coverage suffer from beam squint and pulse dispersion as per Equ and given below[6-10].

Beam Squint in deg is

$$\delta_\theta = \frac{180B}{\pi f_c \tan(\theta_s)} \tag{3}$$

Pulse dispersion not occurs if maximum delay

$$\tau_{max} = \frac{Nd\sin(\theta_s)}{c} << \tau_p \tag{4}$$

Where B is bandwidth, f_c is center frequency, d is inter-element spacing, c is velocity of electromagnetic wave, θ_s is scan angle relative to broadside, N is number of elements, and τ_p is the compressed pulse width. As an example, consider an X band phased array radar with f_c = 10GHz, B = 1GHz, $d = \lambda/2(15mm)$, N = 100, will have τ_{max} of 4.33 ns and δ_θ of 3.3 deg results in image distortion due to beam squint and pulse dispersion when used for imaging over wide scan angles of 60°.

For planar array with m rows, n columns (mxn elements) as shown in Fig. 2 to steer the beam in (θ,φ) direction, in case of phase steering the phase shift required at mn[th] element is given in Eqn (5) and Eqn (6).

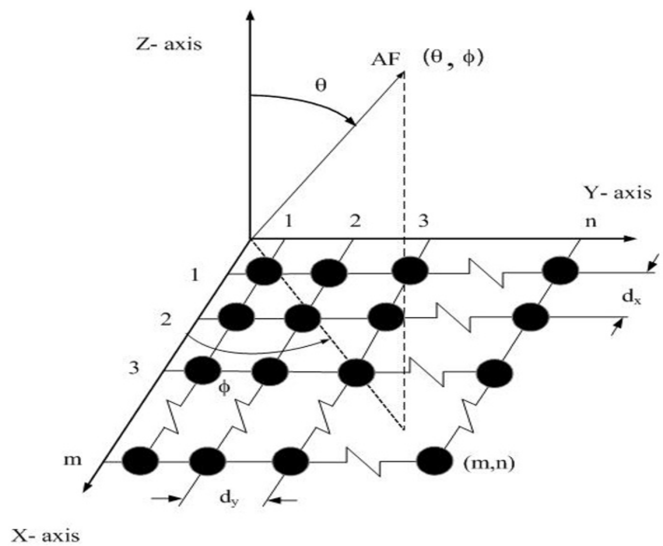

Figure 2. mxn element planar antenna array.

$$Phase = m\times P_a + n\times P_b \tag{5}$$

Where

$$P_a = \frac{2\pi d_x \sin(\theta)\cos(\varphi)}{\lambda}, \quad P_b = \frac{2\pi d_y \sin(\theta)\sin(\varphi)}{\lambda} \tag{6}$$

In case of time steering, time delay required at mn[th] element is given in Eqn (7) and Eqn (8).

$$Time-delay = m\times \tau_x + n\times \tau_y \tag{7}$$

Where

$$\tau_x = \frac{d_x\sin(\theta)\cos(\varphi)}{c}, \quad \tau_y = \frac{d_y\sin(\theta)\sin(\varphi)}{c} \tag{8}$$

Where d_x and d_y are inter element spacing, P_a and P_b are progressive phase shift, τ_x and τ_y are progressive time delay between the elements along X and Y axis respectively, λ is operating wavelength. The maximum time delay (τ_{max}) required for timed arrays (Eq.4) depends on size of the array, inter element spacing, and scan volume coverage. τ_{max}

increases with increase in scan volume, array size (number of elements) and inter element spacing (α wavelength). In conventional phased arrays, the value of phase shift beyond 360° is wrapped around module 2π and a 5 or 6 bit digital phase shifter is used at each element to cover 360°. However, in the case of timed arrays, the progressive time delay across the array cannot be wrapped around. Thus large time delays are required for large size array at higher scan angles. For any phased array, the rms sidelobe level of the array is given in Eqn (9).

$$SLL_{rms} = \frac{\delta_{LSB}^2}{1-\delta_{LSB}^2 \eta N} \tag{9}$$

Where η is tapper efficiency, N is number of elements and δ_{LSB} is the resolution of phase shifter, depends on number of phase shifter bits given in Eqn (10).

$$\delta_{LSB} = \frac{2\pi}{\sqrt{12} \times 2^{Nbits}} \, radians. \tag{10}$$

Since phase, the time delay resolution given in Equ as

$$\tau_{LSB} = \frac{\delta_{LSB}}{2\pi f} \tag{11}$$

where f is the highest frequency of operation. As seen from this equation, the desired SLL of the array decides the time delay resolution. A typical 100 element array in X band requires 5.625° phase shifter resolution for phased array and 1.56ps time delay line resolution for timed array to achieve rms side lobe levels of the order of 40 dB. A typical block diagram of timed array radar is shown in Fig.3, wherein the TTD line replaces the phase shifter at element level in each of the T/R module. TTD line based T/R module block diagram is shown

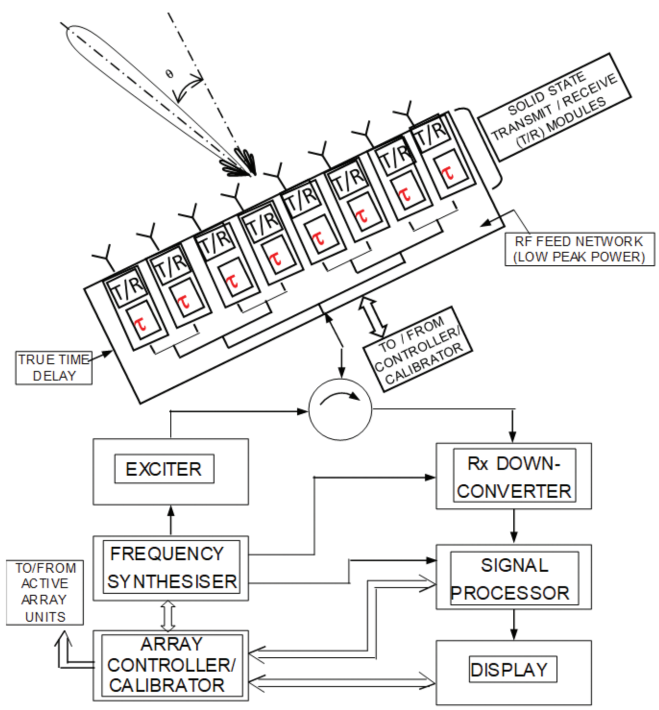

Figure 3. Timed array radar block diagram.

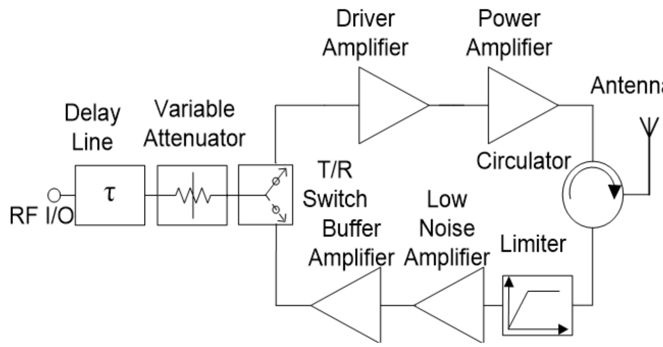

Figure 4. Block diagram of TTD based T/R module.

in Fig.4 uses a single TTD line component shared between transmit and receive path provides required time delay in both transmit and receive modes over wide bandwidth of timed arrays.

TTD line is the key element of timed arrays, which offers frequency-independent time delay over a wide bandwidth. However, TTD lines are bulky, more expensive, and difficult to integrate at the element level. Commercially available TTD lines are limited in maximum time delay and resolution and are not suitable for large arrays.

Other unique methods/techniques are required to be devised for characterization of TTD based T/R modules as well as calibration of the timed arrays, which requires time delay instead of phase measurement used in phased arrays using Vector Network Analyser.

Some of the advantages of timed arrays compared to conventional phased arrays are

- Frequency independent steering and calibration
- Wideband electronic steering
- Less complex Calibration and Beam Steering Networks.

The primary disadvantages of timed arrays are

- Longer time delays due to un wrapping nature
- TTD line components are lossy, bulky and expensive
- Special techniques/methodologies are required for characterisation and calibration.

3. TRUE TIME DELAY (TTD) LINES

The TTD line is a wideband component with a linear phase shift over the bandwidth and time delay is independent of frequency. Generally, TTD lines are switched transmission lines of different lengths or LC circuits.

The TTD line is critical component of timed array and can be loosely grouped into five types based on their basic configuration as Coaxial cables, planar microwave transmission lines, MMIC, Optical/Photonic, and Digital delay lines. The taxonomy of TTD line technology is shown in Fig. 5. The important parameters of TTD lines are given as follows:

- Operating bandwidth
- Maximum time delay and resolution
- Time delay and amplitude flatness
- Switching time
- Power handling
- Control interface (Series / Parallel)
- Size, Weight and Cost

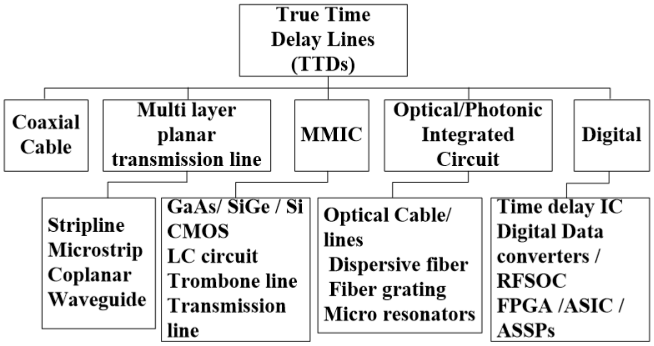

Figure 5. Taxonomy of TTD lines.

As discussed in Sec. 2, the time delay resolution depends on the desired rms side lobe level of the array. The maximum time delay requirement depends on maximum scan angle, bandwidth and size of the array.

The time delay and amplitude flatness over the wide bandwidth affects side lobe level and beam pointing accuracies of timed array. Generally switching time of solid state switches (GaAs FET/CMOS/PIN diode) is in nanoseconds while it is in microseconds for RF MEMS[11] and Optical switches. Time delay line components of T/R module are required to handle maximum power of 20 dBm to 30 dBm.

4. TYPES OF TRUE TIME DELAY LINES

The configuration of different types of TTD lines used in timed arrays is discussed as follows.

4.1 Coaxial Cable Delay Lines

Since time delay is directly proportional to the length of the coaxial cable (one nanosecond per one foot length in free space and 1 nanosecond per 8 inches for PTFE $(\varepsilon_r = 2.2)$ cables, typically 3 meter length of cable is required for 10 nanosecond delay, which will be bulky in size. Further coaxial cables have a frequency-dependent loss (~1:5 dB per 1 meter @12 GHz) and increase of loss with increase in frequency result in more than 5 dB insertion loss variation over a wide bandwidth. Equalizers are necessary for frequency-dependent loss compensation. A programmable time delay line unit can be realized by integrating switched coaxial cables of different lengths, equalizers, control circuitry, etc., which will be bulky in size, expensive, and difficult to integrate as part of T/R modules. Hence coaxial cable types of delay lines are rarely used in timed arrays.

4.2 Planar Microwave Delay Lines

This type of TTD lines uses planar transmission lines viz., microstrip / stripline /Coplanar Wave Guides as basic delay element in place of coaxial cables[12-13]. Time delay of the transmission line is $\tau_d = \frac{l}{v_p}$. Where l is length of the line and $v_p = \frac{1}{\sqrt{\mu\varepsilon}}$ is velocity of wave propagation, depends on permeability (μ) and dielectric constant of the medium. Longer time delay in nanoseconds can be achieved by implementing planar transmission lines in multi layer RF PCB configuration by using high dielectric constant substrates such as Alumina $(\varepsilon_r = 10.2)$ or LTCC (Dupont 951 tape). Time delay (τ_d) in stripline configuration is $33.5\sqrt{\varepsilon}$ ps/cm , microstrip line and Coplanar Waveguide (CWG) is $3.3\sqrt{\varepsilon_{eff}}$ ns/cm. Planar transmission lines of $Z_0 = 50\Omega$ for above types using FR4 substrate $(\varepsilon_r = 4)$ offers time delay of the order of 50 ps/cm to 70 ps/cm[1]. Size and insertion loss of a planar transmission line PCB increases with increase in time delay, and hence difficult to realize them within element grid spacing of the array at higher frequencies. Similar to coaxial cable type delay lines, they exhibit frequency-dependent loss, and hence equalizers are required at wider bandwidths. On the other hand, compared to the coaxial cable type, they are compact in size and low loss. A 5 bit programmable switched transmission delay line (6.2ns max delay) can be realized by cascading five discrete delay line PCBs (0.2ns, 0.4ns, 0.8ns, 1.6ns, and 3.2ns) as shown in Fig. 6.

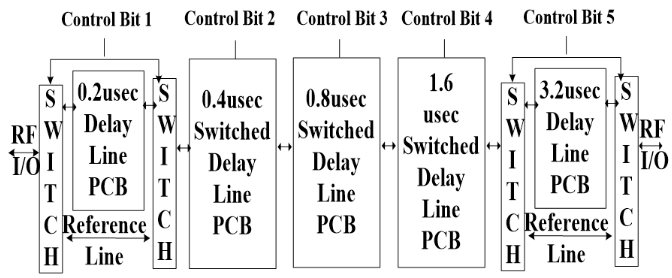

Figure 6. Diagram of 5bit switched planar TTD line.

Insertion loss and dimension of a programmable 5bit switched planar transmission type TTD line using alumina substrate in X band with 4 GHz bandwidth is given in Table 1.

Table 1. Parameters of switched planar TTD lines

Parameters	Specifications
Frequency Range	8 - 12GHz
Time Delay for individual sections	0.2 ns/0.4 ns/ 0.8 ns/ 1.6 ns/ 3.2 ns
Dimensions of delay line section PCB	6 x 6 x 3mm max
Delay flatness over the bandwidth for any delay section	±5 ps or 1% of total delay whichever is higher
Insertion loss	3 to 8 dB+/- 0.5dB for 0.2ns to 3.2ns respectively.
5 bit Switched Delay line	
Time delay	6.2ns max in steps of 0.2ns
Insertion loss	15+/- 0.5dB
PCB dimensions	16x 12 x 4mm max
Switching time (max)	100ns

A hybrid architecture based timed array[14] as shown in Fig. 7 utilizes MMIC based TTD lines with 0.2 ns max delay at T/R module level (τ_1), and distributed switched planar delay lines $(\tau_2, \tau_3, -)$ at sub array levels as part of RF power distribution networks in hierarchical configuration to meet longer time delay requirements.

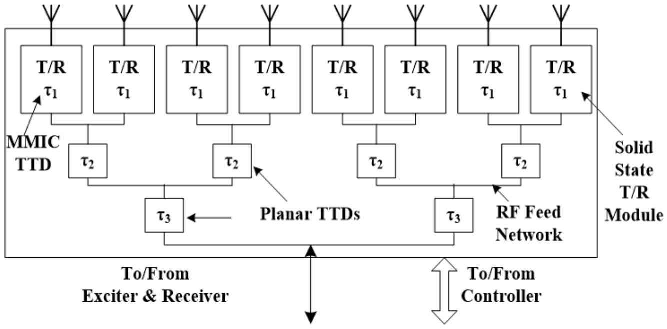

Figure 7. Timed array with distributed TTD lines.

4.3 MMIC Delay Lines

A programmable switched delay line can be realised in Monolithic Microwave Integrated Circuit (MMIC) form by using either GaAs or Silicon/Si-Ge RF CMOS technology. MMIC delay lines are compact in size (~25 mm^2), reliable, and low in cost for a large volume. The delay elements used in MMIC are either LC circuits $\tau_d = N\sqrt{LC}$, where N is the number of LC sections) or constant R networks or transmission line type in trombone-line configuration. A 4bit variable TTD line in MMIC form offers 4 ps to 64 ps delay consists of two sections, a 1-bit 0/32 psec switched delay line and a 3-bit variable delay in trombone-line configuration[4]. A wideband GaAs-based 2 GHz - 20 GHz 6-bit True-Time Delay line MMIC (145ps max delay) is designed using constant R networks to reduce chip dimensions as well to achieve flat time delay is reported[15]. A GaAs based Multi-Function Chip (MFC) integrating 8-bit TTD line (255 ps max delay and 1ps resolution), 7-bit attenuator, and wideband amplifiers on single MMIC over a wide bandwidth of 6-18 GHz is designed using LC circuit as delay element[16]. A CMOS based 6-bit TTD core chip (3.6 psec resolution, 196 ps max delay) integrated with a 6-bit digital attenuator, buffer amplifiers over 4 GHz to 16 GHz is commercially available from RFCORE in unidirectional configuration[17]. MMICs referred above has limited maximum time delay of <500 ps and non reciprocal. These MMICs use serial control interface, compact in size, and easy to integrate as part of T/R modules similar to 6-bit MMIC phase shifters. In the case of non-reciprocal type, two MMICs are required separately, one each in Transmit and Receive path, which increases the cost of the T/R modules. Non-reciprocal TTD MMICs can be converted into bidirectional by using three numbers of SPDT switches, and the same can be shared in between transmit and receive paths of the TR module as shown in Fig. 8 to reduce the cost and complexity of the array[18].

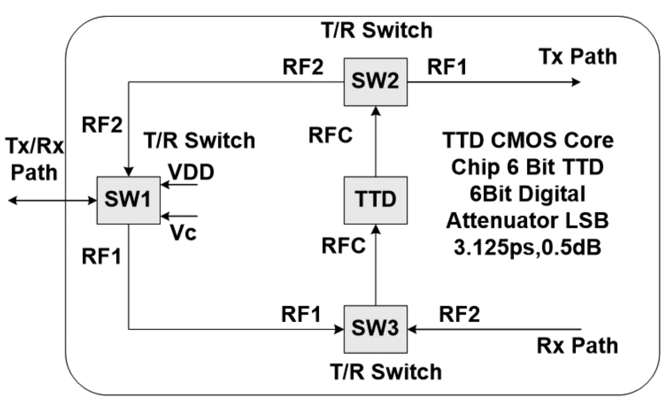

Figure 8. Configuration of bidirectional TTD core chip.

Since MMIC based TTD lines are limited in time delay per chip, multiple chips can be cascaded either at T/R module or at RF distribution network level in a distributed manner to meet large time delay requirement. However, cascading multiple TTD line MMICs will result in ripple in gain over a wide bandwidth. A customized 11-bit MMIC integrating multiple delay sections on a single chip is the better option for large size arrays. The challenges associated with the MMIC type of TTD line are maintaining a constant gain and group delay for all delay settings over a wide bandwidth, implementation in a small chip area, low power consumption, etc., MMIC type of TTD line is commercially available at low cost and widely used in most of the modern timed array radars with improved Size, Weight and Power, Cost (SWaPC) performance.

4.4 Optical/Photonic Delay Lines

This type of delay lines use optical cables, dispersive fibers, ring resonators, fiber bragg gratings, etc., as basic delay line components[19-22]. Optical cables are compact in size, light in weight, wider bandwidth (up to THz) and eliminate EMI/EMC issues in comparison with coaxial cables. Optical cable has ultra low frequency independent loss of the order of 0.4 dB/km and provides five nanosecond time delay per meter length. However, N bit programmable optical time delay line unit require additional RF to optical transceivers for conversion of microwave signals to optical and vice versa, optical switches, splitters as shown in Fig. 9, which increases cost, size, weight, and power consumption.

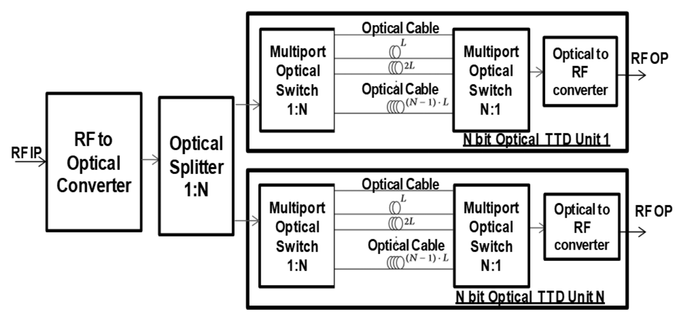

Figure 9. Block diagram of N bit Optical TTD line unit.

The following techniques are reported to reduce hardware:

- Dispersive fibers with Wavelength-division multiplexing (WDM) and micro comb generators (array of laser sources) for implementation of TTD lines[23]. The dispersion type of fibers introduces RF signal fading and wavelength-dependent delay
- Silicon Photonic Integrated Circuit (PIC) based on Switched delay lines using balanced Mach-Zehnder (MZ) switches with different lengths for smaller delay and all-pass filters such as Optical Ring Resonators (ORRs) are utilised for TTD line with 209 picoseconds max delay at 90GHz over 6GHz bandwidth[24].
- Optical true time delay (OTTD) line unit based on Uniform Fiber Bragg Gratings (UFBGs), Photonic Crystal Fiber

(PCF), and Wavelength Converter (WC) is reported[25] and used in ± 69deg steering of array with reduced number of delay lines.

Optical/PIC-based TTD lines are non-reciprocal and require separate delay line units in transmit and receive path, increasing the array's complexity and cost. Moreover, due to low Technology Readiness Level (TRL) and limited spurious dynamic range, PIC delay lines are not widely used at present. However, recent advances in PIC based TTD technology with integrated RF to Optical transceivers (Micro Combs, Photo detectors), optical switches, WDM, fiber grating arrays/optical lines, etc., on a single chip will emerge as promising delay lines with an ultra wide bandwidth (THz) and low propagation loss (0.4dB/km) for future wideband timed arrays.

4.5 Digital Delay Lines

Digital delay line uses registers/D flip flops as delay elements, offers very long time delays of the order of seconds, and finer resolution in picoseconds. At present, Digital Beam Forming (DBF) technology is widely used in radars, EW, and Communication systems, where programmable digital delays can be implemented at FPGA or converter level[26]. The implementation of digital delay requires additional converters (ADCs, DACs, analog Up/down converters, etc.) at each element level to convert RF to digital baseband signals and vice versa, which causes dynamic range limitation, increased power consumption, size, cost, and complexity of timed array system. At higher frequencies with the decrease in inter-element spacing due to short wavelength, it becomes difficult to implement digital delay lines at the T/R module level. However, recent advances in direct RF sampling ADCs/DACs and RFSOCs technology make it feasible to utilize digital lines in wideband arrays. Direct RF sampling ADC/DACs are used up to the S-band. At higher frequencies (>4 GHz), one or two stages of analog Up/down converters are required. Block diagram of digital line implementation in FPGA by using two/three devices at each element level is shown in Fig. 10.

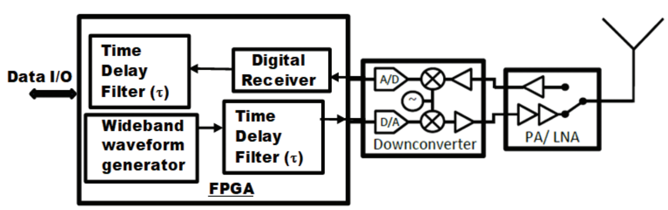

Figure 10. Block diagram of wideband array using digital delay line.

For large arrays, excessive power consumption and high cost of multiple data converters makes impractical implementation of UWB beam forming. However, recent advances as given below in digital converter technologies enable digital TTD lines as a most promising type for future timed arrays.

- Increased RF bandwidth
- Large scale integration of multi analog & digital Up/Down converters, front end TR chips, high speed Interfaces etc., on a single chip
- Multiple beam formation in transmit & receive, re-configurability, frequency independency etc.

5. PERFORMANCE COMPARISION OF TTD TECHNOLOGIES

In early radars, Rotman lens and Bulk Acoustic Wave (BAW) analog TTD lines[8] were used in multi-beam forming and wideband applications, they were bulky and limited in capability. BAW delay lines can provide microsecond delay but associated high transducer conversation loss (acoustic to microwave and vice versa) of 40 dB to 50 dB needs high gain amplifiers for loss compensation. Coaxial cable and planar transmission line types of TTD lines have frequency-dependent loss, bulky, limited

time delay, and not widely used in timed arrays. MMIC types of delay lines are compact in size, low cost but limited both in bandwidth and time delay (few hundreds of picoseconds). Optical cable type of TTD lines offer very low frequency-independent loss over wide bandwidth and longer time delays (few hundreds of micro seconds). Optical delay lines require additional Electrical to Optical (E-O) and Optical to Electrical (O-E) converters as well as due to non reciprocal nature requires separate TTD

lines for Transmit and Receive path of arrays. Photonic Integrated Circuit (PIC) based TTD lines through integrating EO converters, delay elements, and switches on a single chip is a promising choice for future wideband timed arrays with improved SWaPC performance up to THz range. Digital delay lines are widely used in DBF based arrays by offering very long time delays of seconds and require additional frequency-dependent converters (Microwave to digital baseband and vice versa).The recent trends in the development of low power compact size multi-channel direct RF sampling converters and RFSOCs emerge as the most suitable TTD line types for future wideband timed arrays for Radar, EW, and Communication applications. However, PIC and Digital TTD line types are limited in dynamic range, high power consumption, and cost. Customized MMICs with longer time delay and hybrid arrays integrating phase shifters/PCB based delay lines in distributed fashion can be utilized in future large-size timed arrays. Performance comparison of different types of True Time delay lines described in Sec. 4 is summarised in Table.2. The recent advances in MMIC, PIC, and Digital converter technologies enable the fast development of timed array systems in multiple areas.

6. CONCLUSION

As discussed in this review paper, TTD line technology has evolved in leaps and bounds over the past few decades from first generation of Rotman lens to coaxial cable to MMIC to optical and eventually overtaken by the advancements in Photonic and Digital technology. TTD lines which are critical components, dictates scan angle coverage, instantaneous bandwidth, image quality, or Bit Error Rate performance of wideband systems. Thus implementation of timed array technology significantly depends on availability of wide bandwidth, finer resolution, long delay, compact size, low cost and low power consumption TTD lines. At present, the hybrid architecture employing

Table 2. Performance comparison of TTD line technologies

Parameters	True Time Delay (TTD) Line types				
	Coaxial cable	**Planar Microwave transmission line**	**MMIC**	**Optical / Photonic Integrated Circuit (PIC)**	**Digital**
Topology	Switched Coaxial cables	Switched RF transmission lines	Switched lines/LC network /Trombone line	Switched optical cables/ Ring resonators/ FBGs/ Dispersive Fibers	Digital Clock mangers/ Counters/ RFSOCs/Data converters
Bandwidth	Wide (DC-18/40 GHz)	Narrow (Band Specific)	Wide (1-6 GHz/ 4-18 GHz)	Wide (up to THz)	Narrow (up to 4GHz)
Delay Range	Pico to micro seconds	Pico to micro seconds	Hundreds of pico seconds	Pico to micro seconds	Pico to Seconds
Insertion loss	High (~1. 5dB per m @12GHz) and frequency dependent	High (~1dB per m @12GHz depends on substrate) and frequency dependent	Moderate and frequency dependent (compensated through integrated amplifiers & equalizers)	Low (0.4dB/ km) and frequency independent	No loss
Additional Component Requirement	Gain equalizers	Gain equalizers	---	Electrical to Optical & Optical-Electrical Converters	Analog Up/ Down Converters
Volume	Bulky	Medium (delay dependent)	Compact (8x8x1mm typical)	Medium (PICs are compact)	Medium (with converters)
Weight	Heavy	Medium	Low	Medium (PICs - low in weight)	Medium (with converters)
Cost	Medium	Medium	Low (depends on Volume)	High	High
Power Consumption	Very low (mw)	Very low (mw)	Low (1 to 2W)	High (5 to 10W)	High (10 to 15W)
Integration at T/R module level	Not possible	Small delay lines can be integrated	Easy to integrate	PICs can be integrated	In form of ASIC/ ASSPs can be integrated

switched delay lines along with MMIC based TTDs is the most suitable solutions towards implementation of large size timed arrays for high resolution imaging radars. Digital and PIC type true time delay lines are the most promising technologies for development of future ultra wideband systems.

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