J. Eur. Opt. Society-Rapid Publ. 2025, **21**, 2
© The Author(s), published by EDP Sciences, 2025
https://doi.org/10.1051/jeos/2024046
Available online at: https://jeos.edpsciences.org

Journal of the European Optical Society-Rapid Publications

REVIEW ARTICLE **OPEN ACCESS**

A review of research on optical true time delay technology

Ting An*, Limin Liu, Chunhui Han, Sai Zhu, and Yunfeng Jiang

Army Engineering University Shijiazhuang Campus, Shijiazhuang 050003, China

Received 4 August 2024 / Accepted 13 November 2024

Abstract. Light controlled phased array has the advantages of fast response speed, compact system, diverse functions, and flexible control, and has been widely applied in many scientific and technological fields. Optical true delay technology (OTTD) is the most direct technical means to achieve phase delay of optical carrier signals, and it is also the most basic technical means to implement optical controlled beamforming systems. In order to fully understand the optical true delay technology, this article first elaborates on the principle of phased array antennas and the reasons for beam squint, and analyzes the impact of true delay on the performance of phased array radar. Then, the basic principle, technological progress, and related applications of optical true delay are introduced. Taking four common structures of optical true delay lines as examples, which are micro-ring resonant cavity array, grating true time delay line, multi-path switchable optical true time delay line (OTTDL), and wavelength selective optical delay line, their performance in delay accuracy, adjustable delay range, and frequency bandwidth are compared. Finally, the current problems and future development trends of optical controlled beamforming technology were summarized.

Keywords: Microwave photonics, True time delay (TTD), Optical true delay technology (OTTD), Optically controlled beamforming network, Light controlled phased array.

1 Introduction

With the increasing complexity and diversity of detection environments and targets, radar urgently needs to have higher resolution capabilities to achieve precise detection of targets and complete recognition functions [1, 2]. However, traditional radar is limited by the "electronic bottleneck", making it difficult to achieve substantial breakthroughs in expanding operating bandwidth and improving signal processing speed, and increasingly unable to meet the detection needs in complex environments in the future.

Microwave photonics is an emerging interdisciplinary field that combines microwave technology and photonics [3]. Different from traditional electronic microwave systems, microwave signals in microwave photon systems are first loaded into the optical domain through electro-optic converters, then transmitted and processed through optical devices and related links, and finally converted into electrical signals for external transmission [4, 5]. Microwave photon radar utilizes photonics methods to generate and process radar signals, and has outstanding broadband capability, which can significantly improve radar range resolution [6]. In order to improve the radar angle resolution capability and achieve flexible beam control, the combination of microwave photon radar technology and phased array technology is an inevitable development trend [7–10]. Therefore, optical controlled beamforming technology is receiving increasing attention in modern radar applications and future radar development.

Generally speaking, devices and systems that can achieve active array optical field phase control can be referred to as optically controlled phased arrays. With the rapid development of high beam quality light sources [11–13], electronic engineering technology [14, 15], materials science, and optoelectronic devices [16] in recent years, the diverse forms of optically controlled phased array technology have gradually improved and been widely applied in fields such as laser coherent synthesis, optically controlled phased array radar, and atmospheric turbulent calculation [17–20].

2 Principle of phased array antenna and beam squint phenomenon

2.1 Phased array antenna

Phased array antennas achieve beam scanning by generating a certain relative phase shift between the signals reaching each transmitting element.

As shown in Figure 1, N antenna elements are arranged in a linear array with equal spacing [21]. Assuming that the

---

* Corresponding author: `antinghbdl@163.com`

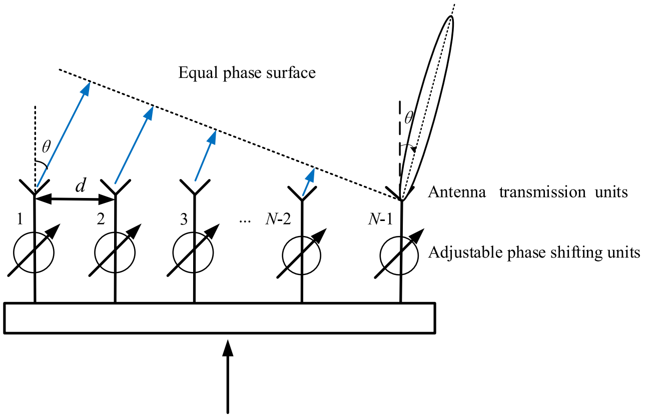


Figure 1. Schematic diagram of phased array.

angle at which the beam pointing power is maximum is θ_0, the phase difference between adjacent antenna elements emitting microwave signals at θ_0 satisfies the following formula

$$\Delta\varphi = \left(\frac{2\pi}{\lambda}\right) d \sin\theta_0 \tag{1}$$

In formula (1), d is the spacing between adjacent elements, and λ is the wavelength of the transmitted microwave signal.

The phase difference between the elements at both ends is

$$\Delta\varphi = \frac{2\pi}{\lambda}(N-1) d \sin\,\theta_0 = \left(\frac{2\pi}{\lambda}\right) L \sin\theta_0 \tag{2}$$

In formula (2), L is the total length of the linear array antenna, which is the distance between the two end elements. According to the principles of antennas and vector field theory, the directional diagram of a one-dimensional linear structure array antenna can be represented as

$$F(\theta) = \sum_{i=0}^{N-1} a_i e^{j2\pi(i\Delta t)^{f(\sin\theta - \sin\theta_0)}} \tag{3}$$

Among them, θ is the antenna scanning angle, a_i is the power value of the radiated signal of each antenna unit, $2\pi f\Delta t$ is the phase difference between adjacent antenna units, Δt is the signal transmission time between adjacent antenna units.

According to formula (3), the directional pattern of the antenna is not only determined by the beam pointing angle, but also by the frequency of the radar signal.

2.2 Beam squint phenomenon

Assuming the center frequency of the signal is f_0 and the maximum scanning angle of the antenna array beam is θ_m [22]. The “spatial phase difference”between adjacent elements at the maximum scanning angle should be

$$\Delta\varphi_0 = \frac{2\pi}{\lambda_0} d \sin\theta_m \tag{4}$$

The “phase difference within the array” between the Nth antenna unit and the 1st antenna unit is

$$\Delta\varphi = \frac{2\pi}{\lambda_0}(N-1) d \sin\theta_m \tag{5}$$

Different from the “spatial phase difference”, this phase difference is the phase difference that needs to be provided by the phase shifter. Assuming that the distance L between the Nth antenna and the 1st antenna is $(N–1)d$, this distance is called the linear array aperture. Since the wavelength of the signal λ is equal to the speed of light c divided by the center frequency of the signal f_0, the phase difference can be expressed as

$$\varphi = 2\pi f_0 T_0 \tag{6}$$

Where

$$T_0 = L \sin\theta_m / c \tag{7}$$

T_0 is called the “aperture transition time” of an array antenna, which is the time difference between the signals radiated by the antenna elements at both ends of the array antenna reaching the target located in the direction of the maximum beam. If the antenna is in the receiving state, T_0 reflects the time difference between the two antenna units receiving the target signal from the maximum scanning angle θ_m direction.

The phase difference within the array φ increases with the increase of the antenna array, and its value can be m times 2π, where m is any integer. If a phase shifter is used to control the antenna pattern, due to the limitation of the phase shift value provided by the phase shifter, the phase shift value generated by the Nth antenna element is:

$$\varphi' = \varphi - 2m\pi \tag{8}$$

The phase shift value provided by a phase shifter usually does not vary with frequency. When the signal frequency increases from f_0 to $(f_0+\Delta f)$, for the target located in the direction θ_m, the phase difference between the echo signal between the Nth unit and the 1st unit will become

$$\varphi_s = 2\pi L(f_0 + \Delta f)\sin\theta_m / c \tag{9}$$

$$\varphi_s = \varphi_{s0} + \Delta\varphi_s \tag{10}$$

$$\Delta\varphi_s = 2\pi\Delta f T_0 \tag{11}$$

It can be considered that the direction of the antenna beam depends on the balance between the “spatial phase difference φ_s” of the antenna array and the “intra array phase difference φ'” provided by the phase shifter, that is, it needs to meet the condition $\varphi_s = \varphi'$. When the signal frequency changes from f_0 to $(f_0+\Delta f)$, then $\varphi_s > \varphi_{s0}$, breaking the balance relationship will cause the beam direction to deviate.

From formula (6) and formula (7), sinθ_m can be calculated as

$$\sin\theta_m = \left(\varphi \frac{c}{2\pi f_0 L}\right) \tag{12}$$

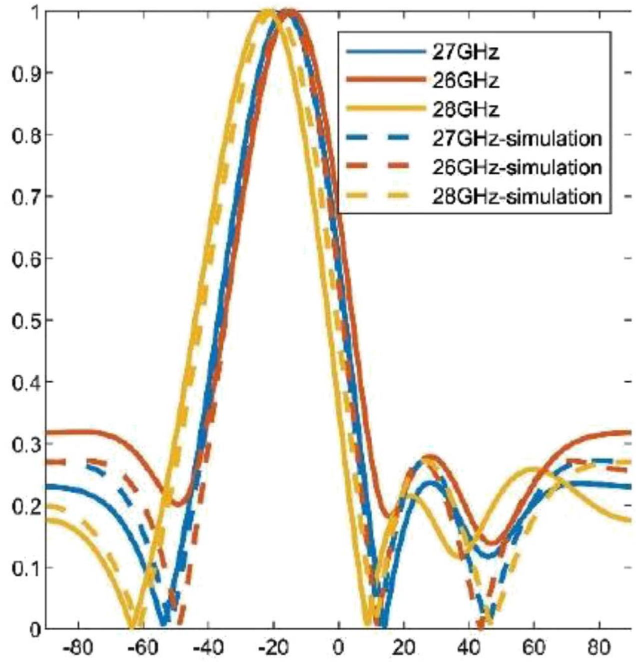


Figure 2. Traditional phased array without optical delay line generates beam squint.

By taking the derivative of both sides and substituting the φ expression in equation (6), we can obtain

$$\Delta\theta_f = -\frac{\Delta f}{f_0}\tan\theta_m \tag{13}$$

According to equation (12), a change in signal frequency will cause a shift in the direction of the antenna beam, and as the signal bandwidth increases, the directional shift $\Delta\theta_f$ also increases. This phenomenon is called the "aperture effect" of phased array antennas, which reflects the spatial oscillation of the antenna beam direction with the change in signal frequency, that is, the beam squint phenomenon, as shown in Figure 2.

The directional diagrams of the antenna are shown in the Figure 2 for operating frequencies of 27 GHz, 28 GHz, and 29 GHz. It can be observed that the beam direction varies with different operating frequencies, with a maximum difference of about 8°, and the antenna sidelobes also vary with different operating frequencies. An important parameter of an antenna is its bandwidth. Here, the limitation for Δf can be referred to as the bandwidth criterion for phased array antennas.

Assuming the maximum allowable beam offset angle is one-quarter of the half power point width of the beam, then

$$\theta_{f\max} = \Delta\theta_{1/2}(\theta_M)/4 \tag{14}$$

$\Delta\theta_{1/2}(\theta_M)$ is the half power point width of the beam when scanned to θ_M, and $\Delta\theta_{1/2}$ is the half power point width of the lobe in the normal direction of the array.

$$\theta_{f\max} = \Delta\theta_{1/2}/\cos\theta \tag{15}$$

Therefore, it can be concluded that

$$\frac{\Delta f_{\max}}{f_0} \le \Delta\theta_{1/2}/(4\sin\theta_M) \tag{16}$$

Among them, $\Delta f_{\max}$ is the maximum bandwidth of phased array antenna. Assuming the above equation is satisfied, the maximum beam offset is $\Delta\theta_{1/2}(\theta)/4$, and when $\theta_M = 60°$, the antenna beam widths are 1° and 2°, respectively. Therefore, the limitation on the signal bandwidth is

$$\frac{\Delta f_{\max}}{f_0} = 0.01 \text{ or } 0.02 \tag{17}$$

Assuming the radar signal is an *L*-band signal with a center wavelength of 1300 MHz, the instantaneous bandwidth of the radar signal is 13–26 MHz, which is far from sufficient for high-resolution measurement and radar imaging radars.

3 The influence of true time delay on the performance of phased array radar

Based on the above analysis, the traditional method of providing phase shift through phase shifters on each elements cannot obtain a large instantaneous signal bandwidth for scanning. To solve this problem, true time delay (TTD) lines can be used for phase shifting at the level of each unit or sub antenna array.

Taking the linear array shown in Figure 1 as an example, the delay line is used to control the phase of the elements in the linear array. The length difference of the delay lines at both ends of the linear array in the Figure 1 is ΔL. Assuming that the delay can fully compensate for the spatial distance difference, and the radar signal pointing angle is θ_m, the relationship between them can be expressed as

$$\Delta L = L\sin\theta_m \tag{18}$$

The pointing angle θ_m is

$$\theta_m = \arcsin\frac{\Delta L}{L} \tag{19}$$

According to formula (19), the pointing angle θ_m is independent of the signal frequency, so the beam pointing remains unchanged.

In fact, for ease of control, the time delay line is usually implemented using a transmission line with a length that is an integer multiple of the wavelength λ, that is, it can only be implemented with $m\lambda$. Therefore, the remaining $\Delta l = L - m\lambda$ delayed over time and the remaining phase residual are compensated by the phase shifter.

If delay line control is applied to each radiating element and a delay line of length l is inserted into the channel of the Nth element, resulting in a delay $T = l/c$, then the delay required to be generated in the i-th element is $i\tau/(N-1)$, and the corresponding delay line length is $il/(N-1)$. Under the action of the delay line, the aperture transition time T_0 of the antenna decreases to

$$\Delta T = T_0 - \tau = \frac{L/\sin\theta_m}{c} - \frac{1}{c} \tag{20}$$

If the beam offset $\Delta\theta'_f$ is allowed to be less than one fourth of the beam width in the θ_m direction, and when $\tau < T_0$, the beam offset $\Delta\theta_f$ can be expressed as:

$$\Delta\theta'_f \le \frac{1}{4}\Delta\theta_{1/2}(\theta_m) = \frac{1}{4}\Delta\theta_{1/2}\frac{1}{\cos\theta_m} \tag{21}$$

The allowed signal relative bandwidth can also be increased, becoming

$$\frac{\Delta f}{f_0} \le \Delta\theta_{1/2}\frac{T_0}{T_0-\tau}\cdot\frac{1}{4\sin\theta_m} \tag{22}$$

Due to $T_0/(T_0-\tau) > 1$, using delay compensation can improve the instantaneous bandwidth of the signal, and the bandwidth limitation on the radar can be expressed as

$$\Delta\theta'_f \le \frac{1}{10(T_0-\tau)} = \frac{1}{10}\cdot\frac{c}{L\sin\theta_m - l} \tag{23}$$

According to the derivation process of equation (23), the beam pointing offset $\Delta\theta'_f$ caused by signal frequency changes can be expressed as

$$\Delta\theta'_f = -\frac{\Delta f}{f_0}\left(1-\frac{\tau}{T_0}\right)\tan\theta_m \tag{24}$$

According to the above equation, when $\tau = T_0$, the instantaneous delay fully compensating for the aperture transition time, the pointing angle shifts $\Delta\theta'_f = 0$, that is, there is no aperture effect. The beam direction of phased array antenna is no longer affected by the instantaneous bandwidth of the signal.

The time delay caused by signal over a single transmission line is called true delay [23], and both true delay and phase shifters are functional devices designed to achieve beamforming. The characteristic of true delay is that its time delay is independent of frequency or the resulting phase shift is linearly related to frequency. The phase response characteristics of phase shifters are generally different from true delay. For example, it does not have linear phase-frequency characteristics like true time delay line. This leads to a fundamental difference between delay lines and phase shifters in practice. In order to achieve broadband wide-angle scanning in phased array radar, TTD should be used instead of the phase shifter in conventional phased array radar. Different from the traditional phase shifters that are only suitable for narrowband operating ranges, TTD can achieve precise control of time delay over a wide operating frequency band.

If microwave signals are modulated onto optical fibers and the fibers are used as TTD, it is called Optical True Time Delay (OTTD). In the optical phased array antenna system based on OTTD, the microwave signal to be transmitted is converted into changes in optical characteristic parameters by an electro-optic modulator firstly. Then, optical methods are used to propagate the optical signal through different optical paths to achieve time delay control. Finally, at the transmitting end, an optoelectronic conversion element is used to restore the optical signal to a microwave signal. As shown in Figure 3, the introduction of optical true delay lines did not result in beam squint.

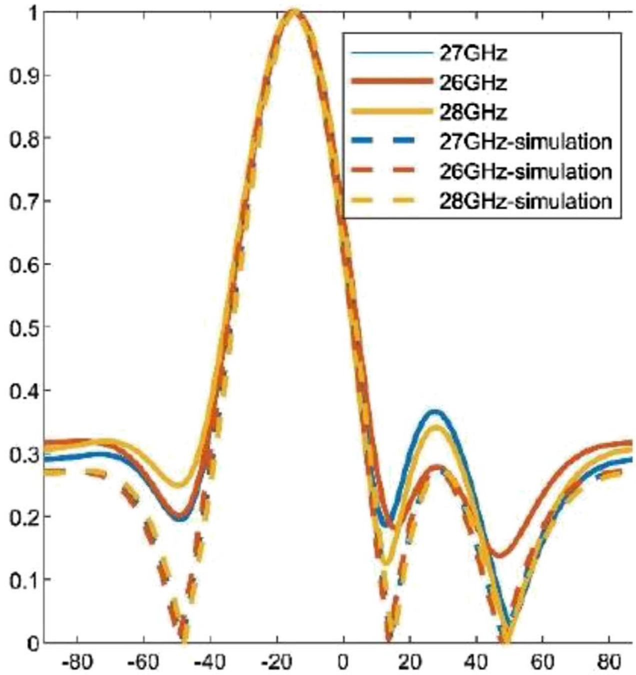


Figure 3. Introducing optical true delay lines does not produce beam squint.

Figure 3 shows the directional patterns of the antenna at operating frequencies of 27 GHz, 28 GHz, and 29 GHz, respectively. It can be observed that the beam direction has not changed and there is no beam squint phenomenon. By comparing Figure 2 and Figure 3, we can conclude that using optical true delay lines can achieve broadband microwave photon beamforming without beam squint, and its operating bandwidth is determined by the flat delay bandwidth of the delay line.

Therefore, in broadband systems, Optical Beam Forming Network (OBFN) has more obvious technical advantages and application potential compared to radio beam forming networks using electronic phase shifters. The optically controlled beamforming scheme is shown in Figure 4 [24].

As is shown in Figure 4, the scheme include five basic units . The first unit is a laser (LD) used to provide an optical carrier for transmitting microwave signals. The second unit is an electro-optic converter (E/O converter), which is used to modulate and convert the input RF signal into an optical carrier signal. The third unit is the Optical Beamforming Network (OBFN), which is used to control the phase delay of modulated optical carrier signals. The fourth unit is the O/E converter, which recovers the optical signal into an electrical signal and obtains multiple coherent microwave signals; The fifth unit is the transmitter/receiver (T/R) component of the antenna unit, which is used to receive and transmit microwave signals.

As mentioned in this section, in broadband systems, OBFN has more obvious technical advantages and application potential compared to radio beam forming networks

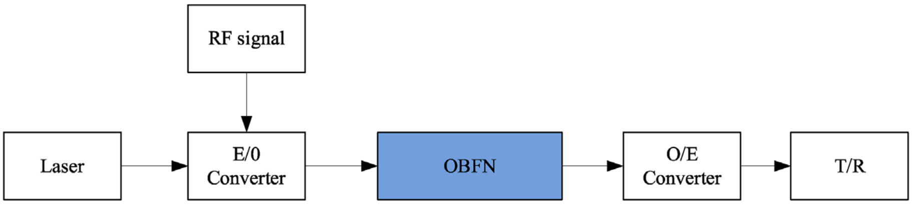


Figure 4. Schematic diagram of optical beamforming scheme.

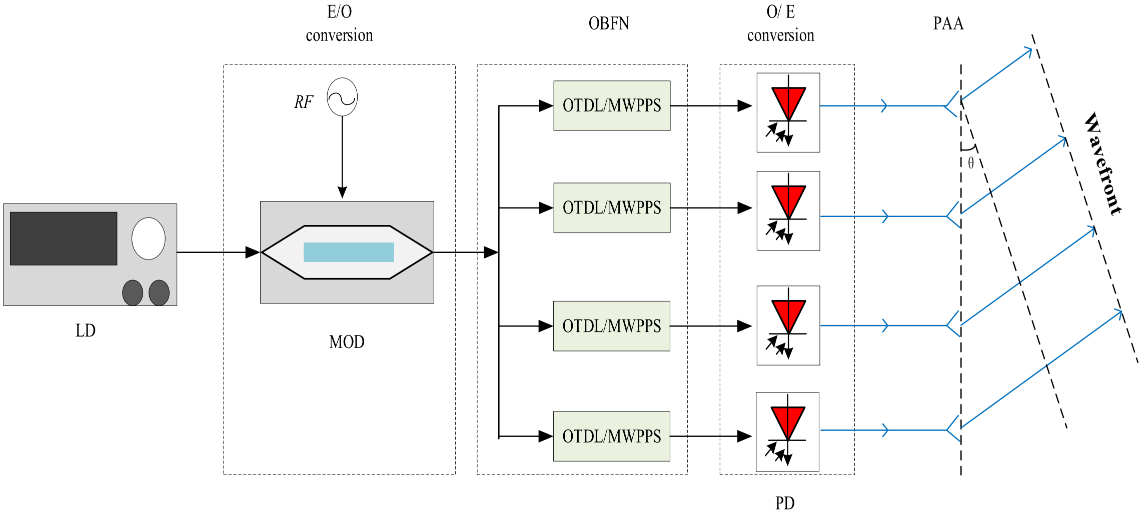


Figure 5. Schematic diagram of a 1 × 4 OBFN phased array antenna system based on adjustable optical true time delay lines or microwave photon phase shifters [23].

using electronic phase shifters. Figure 5 shows a 1 × 4 OBFN phased array antenna system based on adjustable optical delay lines or microwave photon phase shifters.

In Figure 5, the laser (LD) generates an optical carrier, and the RF signal is loaded onto the optical carrier through modulation and conversion to achieve electro-optical conversion. The OBFN consists of Optical True Time Delay Line (OTTDL) and Microwave Photon Phase Shifter (MWPPS). It should be pointed out that the MWPPS controls the phase of the output RF signal by changing the carrier phase. OTTDL delay signals by introducing different transmission times in the signal path, ensuring that signals of all frequencies have the same delay time during transmission. OTTDL is linear and independent of the frequency of the signal. Main function of the OBFN is to operate the OTDD and MWPPS in the optical domain, allocate and transmit them to each antenna element through the distribution network. Finally, use optical detectors to demodulate and recover RF or microwave signals in order to achieve signal transmission in antenna units and beam scanning.

Thanks to the inherent advantages of photonics such as ultra wideband optoelectronic devices, low transmission loss of optical fibers, and resistance to electromagnetic interference, it has great potential for applications in the generation, reception, and processing of high-frequency broadband microwave signals. In recent years, scholars at home and abroad have conducted in-depth research on optical beamforming networks and technologies. Outstanding achievements have been made in areas such as optical true delay lines, microwave photon phase shifters, optically controlled beamforming networks, and their miniaturization.

4 OTTD technology and its research status

OTTD technology is the most direct technical means to achieve phase delay of optical carrier signals, and it is also the most basic technical means to implement optical controlled beamforming systems. There are four common phase delay methods, including three time-domain processing methods and one spectral domain processing method.

It had been summarized that the relationship between the time delay caused by signal transmission in optical fibers and fiber length or refractive index in Reference [25].

$$\Delta\tau(L,\lambda) = \frac{L}{v_g(\lambda)} + \frac{L}{c}\Delta n(\lambda) + LD(\lambda)\Delta\lambda \qquad (25)$$

In formula (25), $\Delta\tau(L,\lambda)$ is the delay time of an optical signal with a wavelength of λ in a path of length L. c is the propagation speed of light and $v_g(\lambda)$ represents the group velocity of the transmitted optical signal. $\Delta n(\lambda)$ is the relative refractive index of the medium material in the path. $D(\lambda)$ is the dispersion coefficient of the medium in the path during propagation of the optical signal, and $\Delta\lambda$ is the wavelength change of the transmitted optical signal.

The three terms on the right side of equation (25) correspond to three time-domain processing methods for optical true delay. The first term means that variable delay can be achieved by changing the total path length L of optical signal transmission, making an optical path difference between each path. This is the most direct method to achieve variable delay. However, as soon as the length of each fiber is determined, it cannot be changed. The second term meas that different delays between different optical channels in the system can be achieved by changing $\Delta n(\lambda)$, which is the refractive index of the dielectric material in the optical path. This delay method is generally used for systems with additional control, such as delay systems with temperature control. However, this method has low reliability and poor operability, making it difficult to achieve high delay accuracy. The third term is that the dispersion of dielectric materials $D(\lambda)$ can be used to achieve variable delay, that is, different wavelengths of optical signals will produce different delays when propagating in the same medium.

The fourth type of scheme for achieving true optical delay is spectral domain processing, which is a true delay scheme based on spatial optical modulation technology. The core of this type of scheme is to convert the optical signal in the time domain into a spectrum in the frequency domain for processing. By using Fourier transform and optical modulation techniques in the frequency domain to adjust the phase and intensity of the signal, to make sure that optical true time delay can be achieved. The advantage of this method is that it can weaken the influence of high-order dispersion in the transmission medium and compensate for the filtering characteristics that may occur in the system [26].

5 Research status of OTTD technology

Continuously improving delay accuracy and achieving as much continuous and adjustable delay as possible are two important aspects of studying fiber optic delay lines. At present, research on optical true delay lines mainly focuses on four aspects: micro-ring resonators, grating delay lines, multi-path switchable optical switches, and wavelength selective optical delay lines.

5.1 Micro-ring resonant cavity array and its principle

The micro ring or micro disk resonant cavity array is an important component of the resonant tunable integrated fiber delay line. Essentially, the slow light effect is realized by generating resonance, thus slowing down the propagation speed of light. Finally, the amount of delay can be adjusted by adjusting the deceleration factor.

5.1.1 Principles and research status of micro-ring resonant cavity array

The slow light effect refers to an important physical effect that enhances the interaction between the optical field and matter by increasing the group refractive index of the waveguide to reduce the group velocity of the optical signal propagating in it. Although the effective refractive index of the waveguide itself changes very little, the group refractive index varies greatly due to the slow light effect. The change in group refractive index can affect the dispersion characteristics of optical signals, thereby affecting the optical bandwidth. By precisely controlling the dispersion characteristics of the medium and the parameters of the optical pulse, it is ensured that the change in group refractive index leads to a reduction in dispersion, which reduces the degree of waveform distortion of the optical signal and is beneficial for reducing the optical bandwidth. On the other hand, due to the slower propagation speed of light in slow light media, the propagation time of light pulses through the medium becomes longer, allowing the system more time to precisely control the delay of light pulses. Therefore, the slow light effect can be used to achieve high-precision time delay. Finally, the slow light effect can significantly increase the delay range. Due to the slower propagation speed of light in slow light media, media of the same length can provide greater time delay. This means that shorter media can be used to achieve larger time delays, significantly reducing the length of optical delay lines and tuning power consumption [27].

In 2013, Burla et al. [28] proposed and implemented an integrated photon beamforming network based on a programmable optical ring resonator, which can achieve continuous adjustable optical delay of 236 ps in the Ku band (10.7–12.75 GHz). However, the adjustment accuracy of the optical true delay line designed using this method is not high. In order to further improve the adjustment accuracy and maximum adjustable range, and enhance the adjustment accuracy of the optical true delay line. Xiang et al. [29] proposed a low loss continuously tunable optical true delay line based on Si_3N_4 ring resonator in 2018, creatively using Side Coupled Integrated Spaced Sequence of Resonators (SCISSOR). The maximum delay of this optical true delay line can reach 500 ps. To expand the working bandwidth, Shan et al. [30] proposed a broadband continuously tunable microwave photon delay line based on cascaded silicon micro rings in 2021. The working bandwidth of the delay line can reach 16 GHz, with a minimum adjustable step size of 20 ps and a maximum adjustable range of 160 ps. Xue et al. [31] (Tab. 1) demonstrated an optically controlled beamforming network based on micro microresonator frequency comb source and dispersion delay. The working bandwidth of this network is 12 GHz, and the adjustable accuracy and range have been further improved compared to Shan et al.'s research.

5.1.2 Brief summary

The advantages of the optical true delay line based on the micro ring resonant cavity array are easy to manufacture, a large adjustable range of optical delay, and the ability to achieve continuous delay. The disadvantage is that the change in deceleration factor is usually thermal regulation, which limits the beam switching time for beamforming using micro ring resonators as delay lines or phase shifters.

Table 1. Comparison of research literature on micro-ring resonant cavity array.

Structure	Delay accuracy/ps	Adjustable delay range/ps	Frequency/GHz	Chip platform	Fabrication complexity	Footprint (mm^2)
MRR [28]	–	0–236	10.7–12.75	TriPleXTM waveguide	Mediate	–
MRR [29]	–	0–500	10	Si_3N_4 waveguide	Mediate	90
MRR [30]	20	0–160	0–16	SOI	High	8
MRR [31]	0.03		8–20	SOI	High	

Note: MRR stands for Miniature Resonant Ring.

Table 2. Comparison of research literature on optical true delay lines.

Structure	Delay accuracy/ps	Adjustable delay range/ps	Frequency/GHz	Chip platform
GDL [33]	6.6	60	10	SOI
GDL [34]	4.7	181.9	10	Si
GDL [35]	0.2	200	8–12	SOI

GDL stands for Grating Delay Line.

5.2 Grating true time delay line

5.2.1 *Principles and research status of grating true time delay line*

Fiber Bragg Grating (FBG) plays a crucial role in fiber delay lines by reflecting or transmitting light of specific wavelengths to achieve delay effects. By adjusting the parameters of the fiber Bragg grating (such as refractive index modulation depth, grating length, etc.), the propagation time and delay of light can be controlled. Common types include true delay lines based on fiber Bragg gratings (FBGs) and linearly chirped fiber Bragg gratings (LCFBGs). In addition, in photonic integrated circuits, silicon-based waveguide gratings can be realized by periodically modulating the effective refractive index of the waveguide, which lays the foundation for the implementation of compact resonant delay lines.

Delay lines based on LCFBGs have achieved significant results in practical applications. For example, a 5-bit delay line based on LCFBG has achieved an average step of 5.39 ps, a delay accuracy of 2.46 ps, and a time delay range of 0–168.6 ps [32].

5.2.1.1 *Principles and research status of grating delay line*

Sun et al. [33] used the stepped chirped subwavelength grating waveguide Bragg grating technology in 2020, which achieved discrete tunable optical delay lines on silicon on insulator. The minimum adjustable step size in this technology is 6.6 ps, and the adjustable range of 10 subwavelength gratings is 60 ps. Sun et al. [33] used 10 subwavelength gratings and Bragg gratings in series to achieve a step structure, and conducted beamforming simulation experiments using FDTD. The simulation used PML as the boundary condition, under which the optical radiation in the propagation simulation area had no effect on the internal field. PML absorbs incident electromagnetic waves, which is equivalent to propagating to infinity. The simulation results indicate that the beams are pointing at 7.56°, 15.13°, and 23.2°, respectively. The limitation of the above research work is that the working bandwidth is relatively narrow.

In order to further expand the work bandwidth, Wang et al. [34] developed an exponentially variable optical real-time delay line based on a 40 sub-wavelength grating waveguide array in silicon on insulator. The delay line achieves a phase shift step size of 4.7 ps and a maximum adjustable time of 181.9 ps within a bandwidth of 10 GHz. Srivastava et al. [35] (Tab. 2) proposed a photon based broadband TTD beamforming network, as shown in Figure 4.

In Figure 4, the lightwave from the tunable laser source is externally modulated by Mach-Zehnder modulator (MZM), the other two input terminals being powered by the RF signal produced by the RF signal generator and the DC signal produced by the modulator driver. The amplified modulated optical signal from the erbium-doped fiber amplifier is then divided equally into four arms by a 1 × 4 optical splitter, and each arm consists of an optical circulator and a raised cosine apodized linearly CFBGs (RCFBG) of distinct lengths and a chirp parameter as a TTD module. The lightwave, whose wavelength corresponds to the chirped grating period, is reflected and reaches the photo-detector (PD) by means of an optical circulator.

In Figure 6, the network uses different lengths ofraised cosine apodized linearly chirped Bragg gratings (RCFBG) and chirp rates as variable TTDs to control the maximum radiation direction of phased array antennas. The experiment shows that the real-time delay line of the light has an adjustable delay accuracy of 0.2 ps and a maximum adjustable delay range of 200 ps. The phased array antenna using this real-time delay line can achieve continuous beamforming in the Ku band, and the main lobe of its directional pattern can be scanned without squint between ±36.8°.

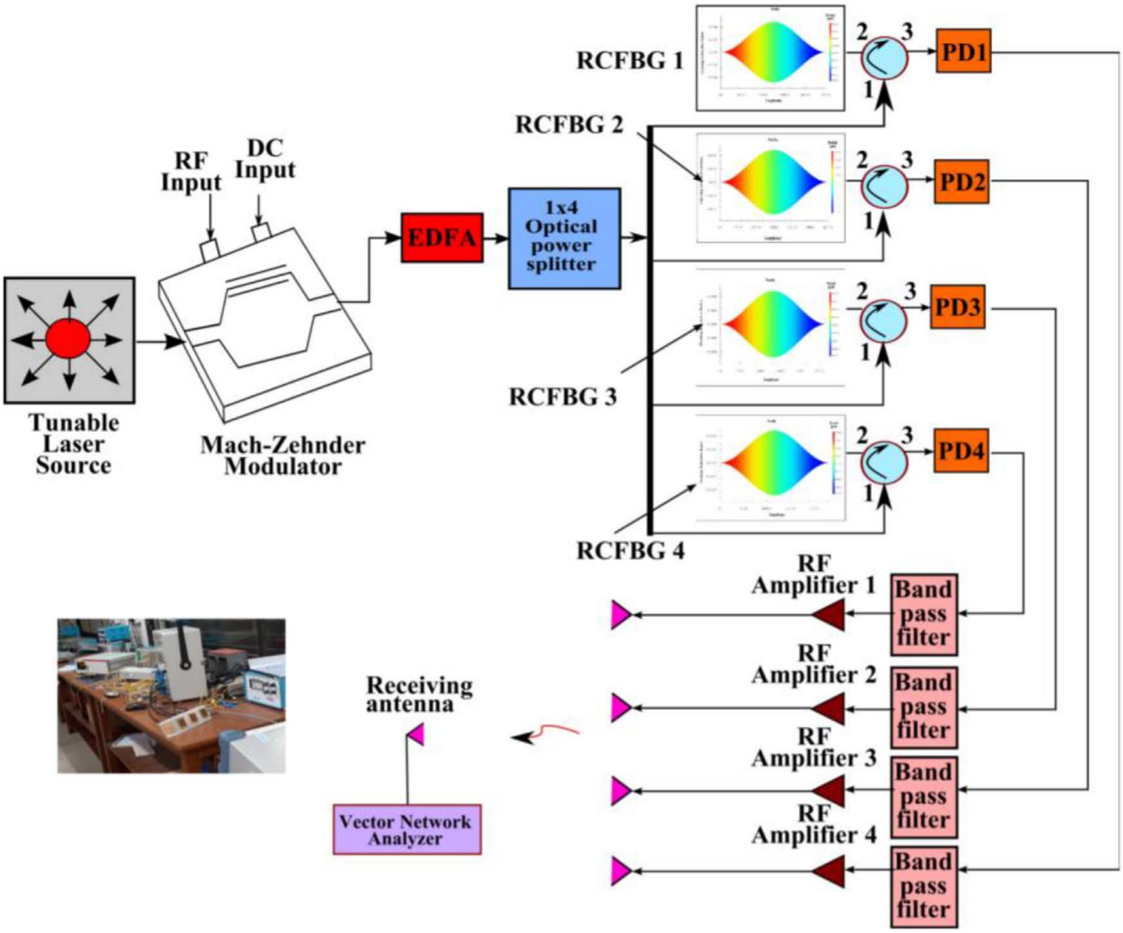


Figure 6. Photon based broadband true delay line beamforming network [35].

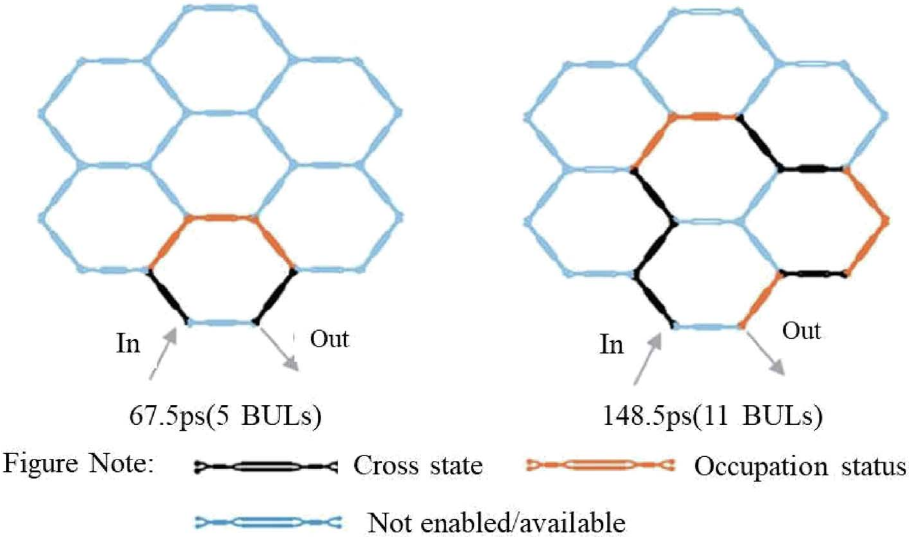
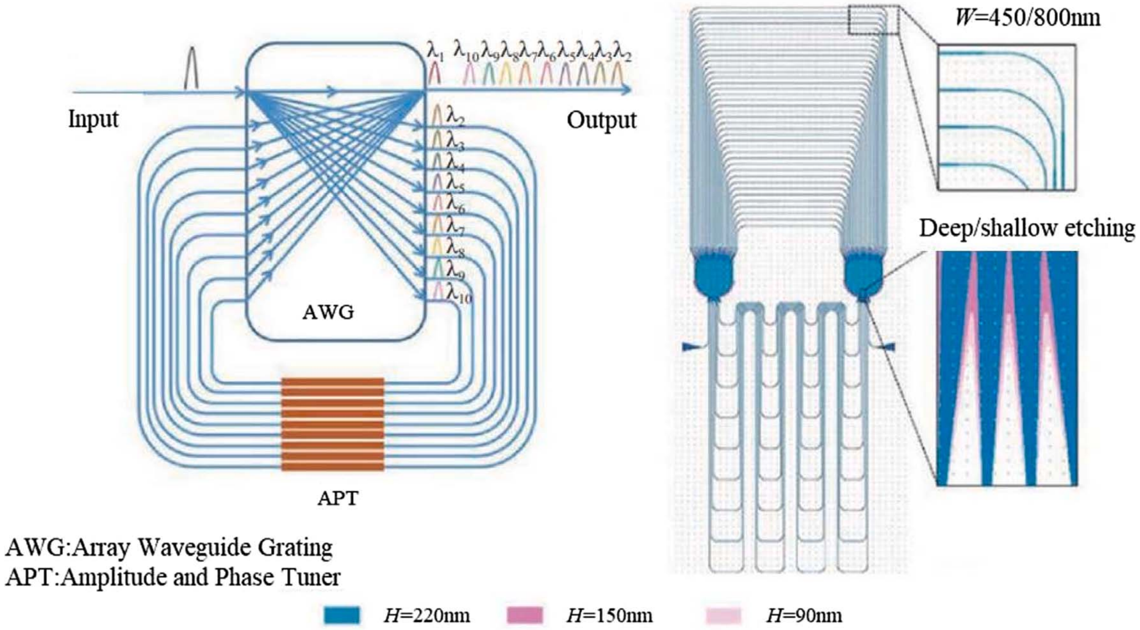


Figure 7. Setting up two different time delays in a 7-unit layout [36].



(a) (b)

Figure 8. Wavelength selective turel-time delay line based on AWG [38]. (a) Working principle explanation (b) AWG layout.

5.2.2 Brief summary

Generally, the advantage of optical true delay lines based on grating spatial structures is that they are easy to integrate, but the disadvantage is that they cannot achieve continuous adjustment or require changing the wavelength of light for adjustment, which will increase the cost of the system.

5.3 Multi-path switchable OTTDL

5.3.1 Principles and research status of multi-path switchable OTTDL

Another way to achieve adjustable delay lines is to adjust the length of the optical path. The adjustable TTD can be achieved by designing optical waveguides with different lengths. The advantage of optical switch technology is that it provides a large delay selection, allowing the module to operate in ultra wide radar frequency bands.

In 2018, Pérez-López et al. proposed a programmable photonic integrated circuit, in which the architecture of the waveguide meshes used can be configured to achieve optical true time delay lines (OTTDLs) [36]. In this article, another independent adjustable unit structure was demonstrated in the experiment, which can achieve independent beam amplitude allocation and phase control with this coupler. Each path corresponds to a latency of 13.5 ps, with a maximum achievable latency of 148.5 ps. Figure 7 demonstrates the hexagonal network configuration with 5 paths and 11 paths.

In 2020, Zhu et al. designed an integrated optoelectronic chip based on a silicon on insulator platform, called a 1 × 8 microwave photon beamformer [37]. The chip consists of a modulator, an eight channel optical beamforming network, and eight photodetectors, containing hundreds of active and passive components. Among them, the phase shifting part adopts eights 5-bit adjustable true time delay lines, with an adjustable range of 2–16 ps and a total adjustable range of 0–496 ps.

In 2023, Sun developed a 4-channel 5-bit programmable optical controlled beamforming network based on a high-precision optical switch delay line measurement and production platform, and conducted experimental tests on the network. The experimental results showed that the delay accuracy was better than ±0.5 ps, which was higher than similar delay lines reported domestically, and the insertion loss consistency was better than ±1 dB [24].

5.3.2 Brief summary

The most obvious advantage of the optical true delay line based on multi-path switchable switches is its fast switching speed, which can reach ns level speeds. This is because the adjustment method of the optical switch is mainly based on the photoelectric effect, which can achieve a speed of ns level. This type of delay line has good accuracy, but the optical delay line of the multi-path switch cannot achieve continuous adjustment.

5.4 Wavelength selective OTTDL

5.4.1 Principles and research status of multi-path switchable true time delay line

Array waveguide grating is a good wavelength selective device. Figure 8 shows the structure and working principle of the wavelength selective optical delay line of the array

Table 3. Comparison of research literature on OTTDLs.

Structure	Delay accuracy/ps	Adjustable delay range/ps	Scanning range	Frequency/GHz	Chip platform	Footprint (mm^2)
MRR [28]	–	0–236	–	10.7–12.75	TriPleXTM waveguide	–
MRR [29]	–	0–500		10	Si_3N_4 waveguide	90
MRR [30]	20	0–160		0–16	SOI	8
GDL [33]	6.6	60		10	SOI	
GDL [34]	4.7	181.9		10	Si	
GDL [35]	0.2	200	−36.8° to +36.8°	8–12	SOI	
PS [36]	13.5	148.5	–	–	–	
OS [37]	2.5	0–96	−75.51° to 75.64°	8–18	SOI	42.8
AWG [38]	10.3	20,000				

Note: MRR stands for Miniature Resonant Ring; GDL stands for Grating Delay Line; AWG stands for Array Waveguide Grating; PS stands for Path Switching; OS stands for Optical Switch.

waveguide grating. By cascading two stacked array waveguide gratings, the delay can be changed by changing the carrier wavelength.

Duan et al. [38] improved the multi-channel programmable optical controlled true delay network by dividing the optical signal into 8 channels of single wavelength light. By modulating signals of different wavelengths and passing them through precision fibers of different lengths, they achieved a minimum delay accuracy of 10.3 ps and a maximum adjustable range of 20 μs for the optical true delay line.

5.4.2 *Brief summary*

The advantages of wavelength selective optical delay lines are easy processing, large adjustable range, and easy integration; The disadvantage is that it requires high continuous adjustability of the laser source [39, 40].

5.5 General analysis

Table 3 compares different kinds of optical true delay lines based on technical indicators such as delay accuracy, adjustable delay range, and scanning range.

Through analysis and comparison, it can be seen that micro ring resonators are easy to fabricate, have a large adjustable range of optical delay, and can achieve continuous delay, while the beam switching time is relatively long. Grating delay lines are easy to integrate, but cannot achieve continuous adjustment or require changing the wavelength of light for adjustment. The switching speed of the optical switch is fast, reaching ns level speed, however the delay accuracy is low and continuous adjustment cannot be achieved. Wavelength selective optical delay lines are easy to process, have a large adjustable range, and are easy to integrate, but require high continuous tunability of the laser source.

6 Summary and prospect

This article has conducted a study on the theory and related technologies of OTTDLs. It elaborates on the principle of phased array antennas and the reasons for beam squint firstly, and analyzes the impact of true delay on the performance of phased array radar. Then, the basic principle, technological progress, and related applications of optical true delay are introduced. Take four common structures of optical true delay lines as examples, which are micro-ring resonant cavity array, grating true time delay line, multipath switchable OTTDL, and wavelength selective OTTDL. Their performance in delay accuracy, adjustable delay range, and frequency bandwidth are compared.

OTTD and MWPPS technology are the main technical means currently applied in optical controlled beamforming systems. With its advantages of low transmission loss and flat broadband response, the diverse forms of optically controlled phased array technology have gradually improved and been widely applied in fields such as optically controlled phased array radar and atmospheric atmospheric turbulent calculation. There are many aspects that need to be tackled.

Analysis of the impact of parameter errors of OTTDLs on array performance. As a relatively complex multi-channel optoelectronic integrated system, OTTDs inevitably has various parameter errors in the processes of manufacturing, deploying and applicating. Therefore, it is necessary to establish a model of the parameter error of OTTDLs with respect to the performance of optically controlled phased array, which provides important support for optimizing array performance and guiding array design.

Miniaturization and integration. For optical beamforming technology, photon integration technology is a necessary path. It is urgent to study the impact of system packaging on the power consumption, temperature, and other indicators of array chips. Thus achieving efficient microwave packaging and system packaging for broadband beamforming networks.

High precision and efficiency. The number, direction, and shape of beams can be more accurately controlled to transmit energy and information more efficiently by improving photonics signal processing techniques or optimizing subarray partitioning algorithms,.

Intelligence and adaptability. Future optical beamforming technology may include more intelligent and adaptive elements. For example, the system can automatically optimize beamforming strategies to adapt to different environments and application requirements by introducing artificial intelligence and machine learning algorithms.

From the development trend of radar technology and microwave photon technology, the application prospects of optical controlled phased array systems and optical true time delay technology in new radar are very broad. The economic benefits and military value generated are incalculable, and its theoretical innovation and engineering application will open a new chapter in detection and perception technology.

Funding

This research was funded by the Military Research (20232B030066) and the 2023 University Youth Independent Innovation Project (KYSZJKQTZQ23013).

Conflicts of interest

On behalf of all authors, the corresponding author states that there is no conflicts of interest.

Data availability statement

This article has no associated data generated.

Author contribution statement

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Ting An, Sai Zhu, and Yunfeng Jiang. The first draft of the manuscript was written by Ting An. The format and content of drafts are regulated by Limin Liu and Chunhui Han. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

References

1 Skolnik MI, *Introduction to Radar*, edited by D. Crispell, 1st edn. (McGRAW-Hill Book Company, New York, 1962).

2 Chen XL et al., Radar low-observable target detection, *Sci. Technol. Rev.* **35**, 11 (2017).

3 Capmany J, Novak D, Microwave photonics combines two worlds, *Nat. Photon.* **1**, 6, 319 (2007).

4 Seeds AJ, Microwave photonics, *IEEE Trans. Microw. Theroy Tech.* **50**, 3 (2002).

5 Pan S, Zhu D, Zhang F, Microwave photonics for modern radar systems, *Trans. Nanjing Univ. Aeronaut. Astronaut.* **31**, 3 (2014).

6 Pan SL, Zhang YM, Microwave photon radar and key technologies, *Sci. Technol. Rev.* **35**, 20 (2017).

7 Zhang MY, *Optically Controlled Phased Array Radar*, edited by J. Liu (National Defense Industry Press, Peking, 2008).

8 Jia CY, Li DW, Ye LH, Phased array radar and optical-controlled phased array radar, *Electron. Dev.* **29**, 598 (2006).

9 Sun HB et al., Development of phased array radar antenna delay technology, *J. Microw.* **37**, 5 (2021).

10 Pan SL, Zhang YM, Microwave photonic radar, *J. Lightwave Technol.* **38**, 19 (2020).

11 Khamees HT, Sameer A, Laser beam blink propagation: evaluation BER in free space resembled dual SLG, *Opt. Lasers Eng.* **171**, 107761 (2023).

12 Khamees HT, Hussein AS, Abdul Khaleq NI, An evaluation of scintillation index in atmospheric turbulent for new super Lorentz vortex Gaussian beam, *TELKOMNIKA (Telecommun. Comput. Electron. Control)* **21**, 1, 1–7 (2023).

13 Khamees HT, Laser Gaussian beam analysis of structure constant depends on Kolmogorov in the turbulent atmosphere for a variable angle of wave propagation, *J. Laser Appl.* **34**, 2 (2022).

14 Esho AO, Iluyomade TD, Olatunde TM, Next-generation materials for space electronics: a conceptual review, *Open Access Res. J. Eng. Technol.* **6**, 2, 51–62 (2024).

15 Carter CB, Ceramics & electronic materials in the Journal of Materials Science, *J. Mater. Sci.* **59**, 5, 1783–1787 (2024).

16 Liu J et al., Eutectic high-entropy alloys and their applications in materials processing engineering: a review, *J. Mater. Sci. Technol.* **189**, 211–246 (2024).

17 Khamees HT, Average intensity of SLVGB for slant path propagation in atmospheric turbulence, *Results Opt.* **5**, 100159 (2021).

18 Khamees HT, Majeed MS, A receiver intensity for Super Lorentz Gaussian beam (SLG) propagation via the moderate turbulent atmosphere using a novelty mathematical model, *J. Opt. Commun.* **44**, s1, s1857–s1864 (2024).

19 Khamees HT et al., Structure constant analyzing of SLG beam Kolmogorov in atmospheric slant path propagation, *AIP Conf. Proc.* **2129**, 1 (2019).

20 Khamees HT, Atmospheric propagation model and affecting on laser beam propagation via free space, Front. Opt. OSA Tech. Digest (2017).

21 Hansen RC, *Phased Array Antennas*, edited by J. Behley (John Wiley & Sons, New York, 2009).

22 Pu T et al., *Principles and Applications of Microwave Photonics*, edited by Q.H. Li (Publishing House of Electronics Industry, Peking, 2015).

23 Yu AL, *Design and Implementation of Beamforming Network Based on Optical Wavelength Division Multiplexing True Delay* (Shanghai Jiao Tong University, Shanghai, 2015).

24 Sun XH, *True Time-Delay Optical Beamforming Technology with Optic Switched Differential Structure and Its Application in Radar Target Direction Finding* (Zhejiang University, Hangzhou, 2022).

25 Huang SG, *Research on Optical Beam Forming System and the Application of RF Orbital Angular Momentum* (Beijing University of Posts and Telecommunications, Peking, 2020).

26 Wang Y et al., Photonics-assisted joint high-speed communication and high resolution radar detection system, *Opt. Lett.* **46**, 24 (2021).

27 Bliek L et al., Automatic delay tuning of a novel ring resonator-based photonic beamformer for a transmit phased array antenna, *J. Lightwave Technol.* **37**, 19 (2019).

28 Burla M et al., Integrated photonic Ku-band beamformer chip with continuous amplitude and delay control, *IEEE Photon. Technol. Lett.* **25**, 12 (2013).

29 Xiang C, Davenport ML, Khurgin JB et al., Low-loss continuously tunable optical true time delay based on Si_3N_4 ring resonators, *IEEE J. Sel. Top. Quantum Electron.* **24**, 4 (2018).

30 Shan W et al., Broadband continuously tunable microwave photonic delay line based on cascaded silicon microrings, *Opt. Express* **29**, 3 (2021).

31 Xue XX et al., Microcomb-based true-time delay network for microwave beamforming with arbitrary beam pattern control, *J. Lightwave Technol.* **36**, 12 (2018).

32 Ren AY, Study of optical fiber delay line based on fiber Bragg grating. School of optoelectronic information, 2016.

33 Sun H, Wang Y, Chen LR, Integrated discretely tunable optical delay line based on step-chirped subwavelength grating waveguide bragg gratings, *J. Lightwave Technol.* **38**, 19 (2020).

34 Wang Y et al., On-chip optical true time delay lines based on subwavelength grating waveguides, *Opt. Lett.* **46**, 6, 1045–1048 (2021).

35 Srivastava NK, Parihar R, Raghuwanshi SK, Efficient photonic beamforming system incorporating a unique featured tunable chirped fiber Bragg grating for application extended to the Ku-band, *IEEE Trans. Microw. Theory Tech.* **68**, 5 (2020).

36 Pérez-López D, Sanchez E, Capmany J, Programmable true time delay lines using integrated waveguide meshes, *J. Lightwave Technol.* **36**, 19 (2018).

37 Zhu C et al., Silicon integrated microwave photonic beamformer, *Optica* **7**, 9 (2020).

38 Duan X et al., Improvement and implementation of a multichannel programmable optical controlled true time delay network, *Opt. Commun. Technol.* **41**, 5 (2017).

39 Niu XY et al., Primary study on time control technology of active phased array based on photoconductive microwave source, *High Power Laser Partical Beams* **35**, 1–7 (2023).

40 Tessema NM et al., *Wavelength-Dependent Continuous Delay Based on a Si_3N_4 Optical Ring Resonator for K-Band Radio Beamformer* (IEEE International Topical Meeting on Microwave Photonics, California, 2016).