Progress In Electromagnetics Research B, Vol. 116, 33–47, 2026

PIER B

(Received 27 August 2025, Accepted 15 October 2025, Scheduled 30 October 2025)

Comprehensive Phase Shifter Review: State of the Art and Future Trends

Sana Gharsalli[1,*], Radhoine Aloui[2], Sofien Mhatli[1,5], Alonso Corona-Chavez[3], Zabdiel Brito-Brito[4], Satyendra Kumar Mishra[4], and Ignacio Llamas-Garro[4]

[1]*SERCOM Laboratory, Polytechnic School, University of Carthage, Tunisia*
[2]*Tunisia Research Laboratory Smart Electricity ICT, SEICT, LR18ES44*
National Engineering School of Carthage, University of Carthage, Tunisia
[3]*Instituto Nacional de Astrofisica, Optica y Electronica, Puebla 72000, Mexico*
[4]*Centre Tecnològic de Telecommunication de Catalunya (CTTC/CERCA), Castelldefels 08860, Spain*
[5]*ISI KEF, 5 rue saleh Ayech, kef 7100, Université de Jendouba, Tunisia*

ABSTRACT: RF signals are widely used in various applications, including radar systems, wireless communication systems, and telecommunications. Phase shifters allow tuning of the signal's phase, using digital and analog designs. This adjustment is essential for antenna beam steering and shaping, signal cancellation, and frequency synthesis in antenna arrays. Phase control is essential to improve the performance of wireless communication and radar systems by enhancing signal reception and transmission. This study examines different types of phase shifters, including a comparative analysis of different phase shifter topologies and technologies, highlighting advantages and limitations according to applications. In addition, this review includes a specific study on liquid metal phase shifters. Finally, the article outlines future research directions for liquid metal phase shifters: It is emphasized that there is a constant need for innovative design strategies to keep pace with the evolving wireless communications and radar fields. Therefore, this article can be a reference for the next milestones in RF phase shifter research.

1. INTRODUCTION

Phase shifters are critical elements in numerous microwave system designs and applications [1], such as phase modulators, harmonic distortion suppression, and beamformers [2]. The most popular application of phase shifters is beamforming using antenna arrays in phased array platforms. Beamforming significantly enhances the link performance of wireless communication systems. In addition, beamforming networks are now widely used in advanced radar systems and evolving 5G communication systems. Beam shaping can be done in the digital, optical, or analog domains [3]. Very flexible beamforming can be done digitally by adjusting the time delay using an analog-to-digital converter (ADC). However, some major drawbacks of digital beam-forming techniques are high cost, increased system complexity, and high loss in applications with a large number of antennas (such as massive MIMO) [4]. In analogue beamforming, two main technologies can be found: passive and active designs. Passive phase shifters include all classes of phase shifters that consume no power when inactive. However, they may consume power when changing the signal phase using, for example, MOSFET transistors. These components use very little power when they are in idle mode. Active phase shifters, on the other hand, are implemented using high-current circuits such as variable gain amplifiers or Gilbert cells. The trade-off for high linearity achieved with passive phase shifters is high insertion loss (IL), noise figure (NF), and large on-chip space requirements. Active phase shifters generally occupy smaller physical areas than passive designs since they can eliminate the need for large components like inductors. Active phase shifters can provide low IL and often incorporate variable gain amplifiers (VGAs), allowing for gain control, which enables amplitude adjustment in addition to phase shifting. However, active phase shifters do have some drawbacks, like decreased linearity compared to passive designs, and power consumption, as they require biasing for active components [5]. In general, passive devices exhibit a significantly lower noise figure compared to active devices. Phase shifters need to be small, inexpensive, and have little IL within the intended bandwidth. The phase shifter size is a crucial element because of space constraints, especially when it comes to portable microwave devices. About half of the system cost is attributed to the development of high-resolution monolithic microwave integrated circuit (MMIC) phase shifters, which are still difficult to implement in tiny phased array formers [6]. Since the performance of phase shifters mainly depends on the technology used for their implementation, this paper studies various topologies/types of phase shifters based on their phase tuning mechanisms and techniques, focusing on their advantages and limitations.

2. THE PHASE SHIFT THEORY

A phase shifter keeps a signal's amplitude while controlling the phase, so it is crucial in RF, microwave, and optical systems.

* Corresponding author: Sana Gharsalli (gharsallisana2@gmail.com).

doi:10.2528/PIERB25082704

Published by THE ELECTROMAGNETIC ACADEMY

There are many uses for phase shifters, such as phased array antennas, beamforming networks, radar systems, and optical communication systems. There is a lot to learn about phase shifting in this section, including how it works, types, and key performance metrics.

2.1. The Principle of Phase Shift

A phase shifter is an electronic device that modifies an electromagnetic wave's phase angle without changing its amplitude. To precisely match other signals or system needs, it adjusts a signal's time. Phase shifters are crucial components in microwave and radio frequency (RF) systems, allowing precise control and manipulation of signal phases. Phase shifters play a crucial role in enhancing signal processing efficiency by enabling precise timing and synchronization of signals, which is essential for maintaining system performance and reliability in various electronic applications. A phased array system's fundamental component is an RF phase shifter. The input signal's transmission phase is adjusted using a control element. This can be accomplished either actively or passively. Phase shifters are used in many different applications outside phased array antenna systems, such as image rejection receivers [7], linearization of amplifiers [8], and as part of electrical testing devices such as signal generators [8]. Changing the phase of an incoming signal, ideally without altering its strength and frequency, is the main function of a phase shifter. Accordingly, an ideal reciprocal phase shifter with Φ phase shift has the following scattering matrix:

$$S = \begin{bmatrix} 0 & e^{j\varphi} \\ e^{j\varphi} & 0 \end{bmatrix} \tag{1}$$

Even though ideal phase shifters only change the signal phase, as demonstrated by Equation (1), practical RF phase shifters suffer from performance degradation. Several parameters can determine the performance of an RF phase shifter, including the bandwidth, IL, return loss, linearity, power handling, phase range/resolution, phase error, chip area, and power consumption. Linearity serves as a crucial parameter in the design of RF phase shifters. To prevent intermodulation effects and subsequent challenges in signal demodulation at the receiver's end, it is essential that the output power level changes consistently in relation to the input power. Similar to amplifiers, the linearity of an RF phase shifter is typically evaluated using its third intercept point (IP_3), which can refer to either the input (IIP3) or the output (OIP3). Naturally, passive phase shifters exhibit greater linearity compared to their active counterparts, which incorporate active devices that are fundamentally non-linear [9].

2.1.1. Resolution and Phase Range

Equation (2) indicates that the phase range is the phase difference between the reference phase (φ_{ref}) and maximum possible phase shift ($\varphi_{\max}$).

$$\varphi_{range} = \varphi_{\max} - \varphi_{ref} \tag{2}$$

The reference value can be subtracted from the actual phase shift to normalize the phase state φ:

$$\Phi = \varphi - \varphi_{ref} \tag{3}$$

The reference value can be subtracted from the actual phase shift to normalize the phase state φ:

$$\Phi = \varphi - \varphi_{ref} \tag{4}$$

The resolution of a phase shifter is the smallest phase shift value that separates two successive phase states. Resolution is a helpful characteristic, especially for digital phase shifters or phase shifters with digital phase control. It is expressed as follows, and it depends on the number of bits N of the phase shifter design [6]:

$$\varphi_{resol} = \frac{\Phi_{\max}}{2^N} \tag{5}$$

The max phase range is 360°. With a 2-bit phase shifter, the resolution is $\Phi_{resol} = 90°$, and the potential phase states are $\Phi_1 = 90°$, $\Phi_2 = 180°$, $\Phi_3 = 270°$, and $\Phi_4 = 360°$. The number of control bits is occasionally used to express resolution. The resolution of many digital phase shifters used in real applications can reach up to 8 bits, and their phase range is 360°. Analog phase shifters rely on the constant analog control voltage to determine their resolution, whereas digital phase shifters have a limited resolution [10], as inferred from Equation (5).

2.1.2. Power Handling

Power handling is an essential parameter of phase shifters, particularly in high-power applications like satellite communications and radar systems. It describes the highest RF power that a phase shifter can withstand without suffering physical irreversible damage or appreciable performance deterioration. Due to transistors' limited P1 dB compression point, passive phase shifters are better at handling power than active phase shifters [6]. It is important to consider power handling when designing RF phase shifters, especially for high-power applications such as radar, satellite communication, and electronic warfare. Because passive phase shifters do not have active components, they have higher breakdown voltages, and they are more thermally stable, whereas active phase shifters have nonlinear transistors and compression effects. When choosing phase shifters, you must think about power requirements, thermal management, and frequency-dependent performance.

2.1.3. Phase Errors

According to [11], the RF phase shifter's phase error is the difference between the desired and measured phase shifts.

$$\epsilon_{\varphi} = \Phi - \Phi_0 \tag{6}$$

where the measured and desired phase states are denoted by Φ and Φ_0, respectively. The accuracy of the phase shifter is frequently assessed using the Root Mean Square[1] (RMS) phase error. Every potential phase shift is used to calculate the RMS error.

[1] Root Mean Square

2.1.4. Surface Area

The size of a phase shifter is an essential consideration that must be managed effectively. RF phase shifters are often quite large due to the significant space required by inductors commonly used in their design. Area consumption for passive phase shifters is primarily determined by their operating frequency, process technology, and resolution/phase range. For lower operating frequencies and higher phase resolution, their circuit size is larger [6]. In contrast, active phase shifters often take up less space than their passive counterparts because they use area-effective blocks like attenuators and active blocks like amplifiers for phase tuning [6]. In order to achieve a balance among performance, integration, and application-specific requirements, the RF phase shifter design needs to be managed effectively. The passive phase shifters may be more effective in high-power applications, but they're bulkier at lower frequencies. Active phase shifters are more space-efficient than passive ones because they employ smaller tuning elements such as varactors and amplifiers. Integrated circuit phase shifters, such as CMOS, GaAs, and MEMS designs, are getting smaller and more effective because of the rapid advancement of technology.

2.1.5. Power Consumption

Like other radio frequency modules, phase shifters should have low to no DC power consumption. However, many active phase shifters conduct phase adjustment using VGAs (Variable-gain amplifiers), resulting in decreased DC power usage. Amplification is also necessary for certain phase shifters to increase the signal's strength and quality. Consequently, the amount of used DC power rises. In contrast, digital phase shifters usually use very little DC power because they mostly use passive components such as capacitors and inductors, which don't require voltage consumption.

2.1.6. Figure of Merit

The figure of merit (FOM) typically represents the performance of frequency-aggressive phase shifters [12]. This number, which is expressed in dB, is the ratio of the relative phase shift measured under control to the IL ($IL = -20\log_{10}|S_{21}|$):

$$FOM_{\text{dB}} = \frac{\Delta\varphi_{\max}}{|IL|} \tag{7}$$

An alternative FOM is calculated as the ratio of the maximum phase shift to the length of the line (L). It is expressed in cm and evaluates the component's effectiveness based on its size [13]:

$$FOM_{\text{cm}} = \frac{\Delta\emptyset_{\max}}{L} \tag{8}$$

However, FOM does not consider several important criteria, such as volume or applied voltage value, and therefore should not be the only point of comparison between tunable phase shifters [14]. RF phase shifters are classified according to the technology used for their implementation, and include mechanical, ferromagnetic/magnetic, micro-electromechanical systems (MEMS), and electronic phase shifters that are based on a phase tuning mechanism. The components or building blocks of RF phase shifters are used to classify them as either passive or active. Also, depending on the control voltage, phase shifters can be either digital or analog. However, this usually means electronic phase shifters [6]. The next part talks about the different kinds of phase shifters and how they are set up.

2.2. Phase Shifters as Key Components in Phased Array Systems

Phase shifters are very important for low-loss beam steering or scanning because they are a key part of phased array antenna systems. Phase shift and IL must meet the following performance requirements [15].

1. mm-Wave phase shift of 0–360° or 0–180° achieved without exceeding IL limits.
2. Over the whole phase shift range in the target frequency band, the IL variation is negligible. With bias control, the IL fluctuation is minimal. In order to reduce beam distortion during antenna beam steering, this is done. The signal amplitude in each channel has a considerable impact on signal combining and nulling in unwanted directions; therefore, the phase shifter needs to have both low IL and consistent loss across its phase tuning range [16].
3. High phase shift resolution.
4. Control is facilitated by factors such as low frequency or DC bias, along with a linear phase shift-voltage response and minimal power consumption, exemplified by a bias voltage of less than 10 V [16].
5. Fast response.
6. Robust, reliable (for instance, capable of functioning in humid conditions and varying temperatures).
7. High power handling capacity (needed for high-power, low-loss transmitters).
8. Compact for being integrated with other components and subsystems.

A phased array transceiver can use this low-loss, high-tuning-range phase shifter technology to perform several tasks, including 5G mobile communications (57 GHz–66 GHz in Europe), satellite communications (60 GHz), gesture sensing (60 GHz), and car radar (76 GHz–81 GHz), among others [16].

Figure 1 shows the basic block diagram of a phase shifter application.

2.3. Topologies

As mentioned in the first section, phase shifters are essential components of millimeter wave and microwave systems because they control a signal's phase. These components' performance characteristics, such as phase shift range, bandwidth, and IL, are directly influenced by their circuit configuration, or topology. Topologies that are frequently used include:

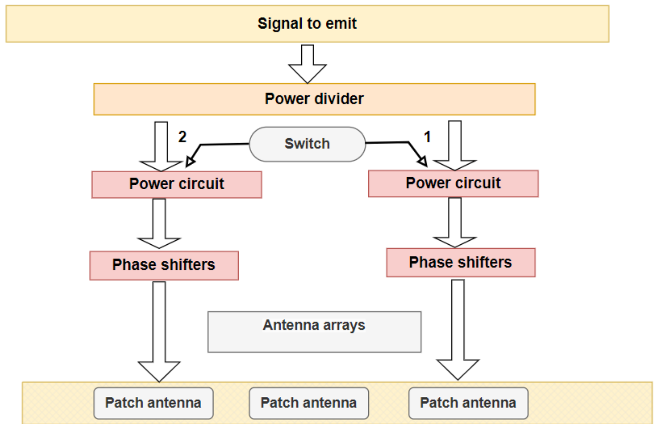

FIGURE 1. Block diagram of common phase shifter application in antenna phased arrays.

- Transmission Line Phase Shifters
- Ferrite Phase Shifters
- Reflective Load Phase Shifter (RTPS)
- Hybrid Coupler Phase Shifters
- Semiconductor Phase Shifters
- Digital Phase Shifters

Numerous research projects have explored different types of phase shifters. This section will discuss and elaborate on relevant designs. To begin with, a brief definition of a phase shifter based on a comprehensive literature review is provided.

2.4. Types

Phase shifters can be categorized into three primary groups based on how the phase-shifting functionality is implemented: digital, optical, and analog.

2.4.1. Digital Phase Shifters

State switching is made possible by digital phase shifters, which discretize the phase into predefined phase states by digitally managing each phase-shifter bit. The bit count of the digital phase shifter determines how many phase states the system can switch between. Accurate state alteration is one of the most crucial features of digital phase shifters. Several methods have been used to implement digital phase shifters.

1. **Microelectromechanical systems (MEMS):** The primary feature of MEMS is its ability to perform electrical and mechanical activities. Their architecture is mechanically flexible and/or movable in response to pressure, electrostatic, thermal, piezoelectric, or magnetic pressure. Electrostatic control is the most utilized actuation method in microwave applications. Switches and radio frequency variable capacitors are the two main applications being pursued. Both devices operate under the same concept [17, 18].

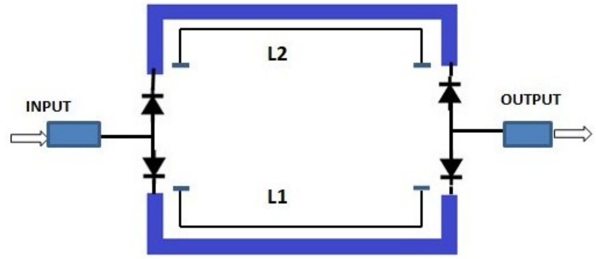

FIGURE 2. A switched line phase shifter's basic schematic [19].

- **Switched line phase shifters**: The switching line implementation is the simplest of all phase shifters in terms of methodology and design requirements. Their losses are similar to the total losses of lines and switches. SPNTs (Single Pole N Throw) switches can be used in either a series or parallel configuration to construct this kind of phase shifter. In Ka-band, 90° and 180° phase shifters with phase delay lines were constructed [19, 20]. Figure 2 illustrates the simplest version of the Switched Line Phase Shifter (SLPS), which uses four Single Pole Single Throw (SPST) switches to transmit signals between two transmission lines of varying lengths, thus different phase shifts. Phase shifter size reduction can be achieved using fractal designs [21, 22]. Equation (9) gives the differential phase shift between the two-phase shifter states.

$$\Delta\Phi = \beta(L_2 - L_1) \tag{9}$$

Figure 3 illustrates the schematic layout of a typical RF-MEMS three-bit switched-line phase shifter with a MEMS series switch. The sequence displays three distinct segments, or bits, each of which generates linearly cascading phase shifts of 30°, 60°, and 120°. Every section (bit) has switching elements, delay lines, and a reference line. The delay line generates the necessary phase shift, such as 30°, 60°, or 120° phase shifts, and the reference line has a phase shift of 0°. This allows for the independent selection of each transmission line segment in order to attain a predetermined phase shift value at the output. For example, the first and third bits must be chosen to produce a phase shift of 180° [23]:

- **Loaded line phase shifters**: The general idea of loaded line phase shifters dates back to the early

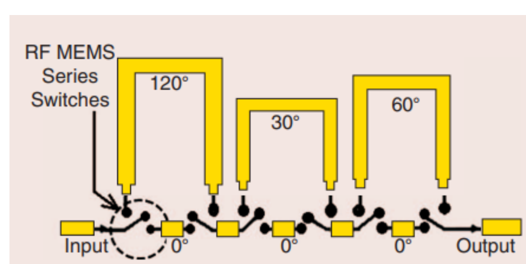

FIGURE 3. The switched-line phase shifter's schematic layout [23].

1960s and has been described in several research publications [24, 25]. Both digital and analog phase shifters can be realized by employing the loaded line technique, which is similar to the switched-line method. The phase shift mechanism of this circuit is based on a transmission line with a low reactance. More specifically, the design concept is to load a transmission line with two distinct impedances. A central line segment that connects the phase shifting sections may be utilized as a matching network to maintain input and output impedances close to 50 Ω, as shown in Figure 4.

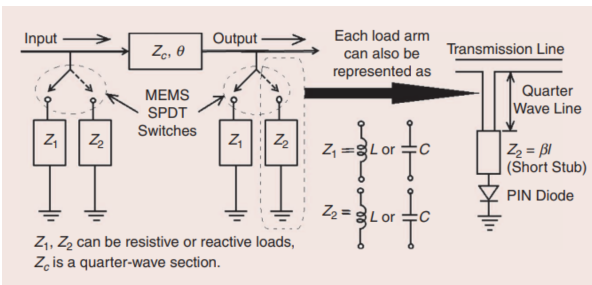

FIGURE 4. The load-line phase shifter's basic schematic [24].

Radial stubs are used in microstrip technology to connect to MEMS switches located at regular intervals along the line. The phase shift occurs as a result of their simultaneous switching [24].

- **Reflection phase shifters**: As demonstrated in the earlier examples, RF MEMS-based reflection-type phase shifters can be constructed in both digital and analog formats; however, the analog format is not frequently used because of its intricate design. Unlike switched-line and loaded-line phase shifter implementations, reflection phase shifters use 3-dB hybrid couplers as one of their primary components, as illustrated in Figure 5.

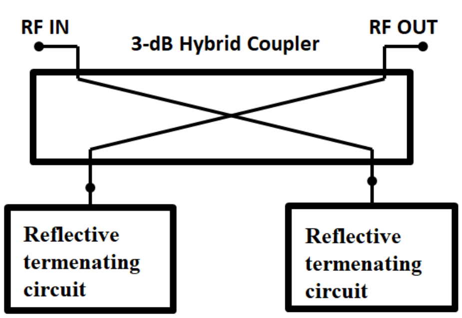

FIGURE 5. A reflection-type phase shifter's schematic diagram [26].

- **Based distributed-line phase shifters**: The distributed-line phase shifter, or more specifically distributed MEMS transmission line (DMTL) phase shifters, are the most widely used RF MEMS-based phase shifters. The bulk of research about MEMS-based phase shifter designs that is still being studied falls into this category. The way they work is that passive parts, such as switched capacitors or varactors, periodically load a transmission line, such as a CPW or microstrip line, to create a phase shifter.

2. **Transistors**: In [27], transistors were used as switches, while resistors and capacitors were used to create the phase-shifting function. Compared to passive designs, in active phase shifters [28], differential phases are obtained using transistors rather than passive networks. This results in high integration with high gain and accuracy, as well as fine digital phase control under a constrained power budget.

3. **PIN diodes**: These are frequently used to regulate the phase shift of signals in digital phase shifters. When used as a switch in digital phase shifters, the PIN diode can be biased either forward or backward. A forward-bias PIN diode allows current to flow through it and functions as a low-resistance switch. The diode has a high impedance and operates as an open switch when reverse-biased. To produce distinct phase shifts, phase shifters use a large number of PIN diodes. The biasing status of every PIN diode is influenced by a different control signal. In discrete states, the phase shift can be controlled by turning on specific diodes in each design. In Figure 6 [29], the PIN diodes were modeled as separate components representing forward and reverse states. Loads were produced utilizing a single inductor coupled in parallel with PIN diodes, eliminating the need for high-isolation diodes.

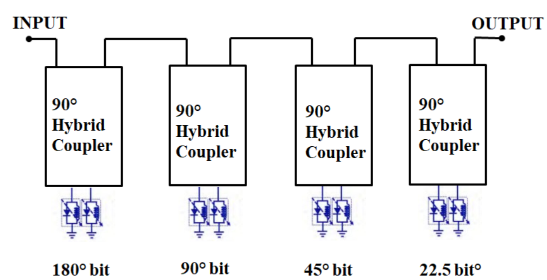

FIGURE 6. 4-bit PIN diode reflection-type phase shifter configuration [29].

2.4.2. Optical Phase Shifters

In many different RF over-fiber applications, optical phase shifters are essential. The advantages of using optical phase shifters for microwave systems include a wide bandwidth, superior isolation, resistance to electromagnetic interference, and the ability to remotely activate an antenna [30]. Optical phase shifters are implemented using optical delay lines [31]. Despite this, optical phase shifters require a large number of optical switches, which significantly increases the overall cost and complexity of the system [28]. Numerous works have been proposed to achieve integrated optical switches. A thermo-optic effect [32] or MEMS actuators [33] are two examples of principles that are frequently used for optical switches to achieve high

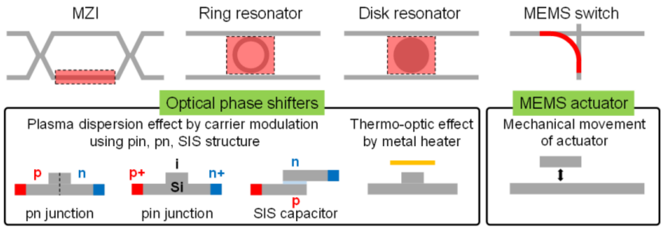

FIGURE 7. Schematics of different optical switches in Si PICs on a large scale [35].

scalability and low crosstalk, although electro-optic effects are the main modulation principles for optical modulators [34]. As illustrated in Figure 7, an optical phase shifter is inserted into the interferometer or resonator structures in the case of electro-optical and thermo-optic switches. As a result, effective modulation schemes covered in earlier chapters are also partially effective for high-performance optical switches. In contrast, each optical pass is connected by mechanically moving the MEMS actuators of MEMS optical switches made of silicon-on-insulator (SOI) or poly-Si.

2.4.3. Analog Phase Shifters

Another significant type of phase shifter is an analog one, which alters the phase of an input signal using analog circuits. Many different types of phase shifters have been made using this concept.

1. **Ferrite phase shifters**: The magnetic properties of ferrite materials are used by these conventional analog phase shifters to create phase shifting. Ferrite phase shifters are based on the Faraday effect and how a magnetic field interacts with microwave signals [36, 37]. Since they offer fine phase control at moderate to high levels, ferrite phase shifters have been utilized in microwave power applications for more than 20 years. However, because this type of phase shifter is usually large and power-hungry, it is not appropriate for small and low-cost microwave systems. For more than 20 years, ferrite phase shifters have been employed in applications requiring precise phase control. According to [38], a typical ferrite phase shifter is illustrated in Figure 8.

2. **Solid-state phase shifters**: These phase shifters modulate signals and regulate the phase shift using solid-state electronic components. Because they do not require expensive digital equipment in the network, they are less expensive to run. In order to enable low-cost and downsized microwave systems, a significant amount of research and development has been directed towards these [23]. PIN diodes [23, 38], varactors [39, 40], tunable inductors, transistors, and MEMS devices are a few examples of these shifters. Typically, the voltage applied to the tuning elements is changed to modify the phase shift within a certain [40–44].

    - PIN diodes typically operate as switches, preserving two separate states "ON" and "OFF" that produce

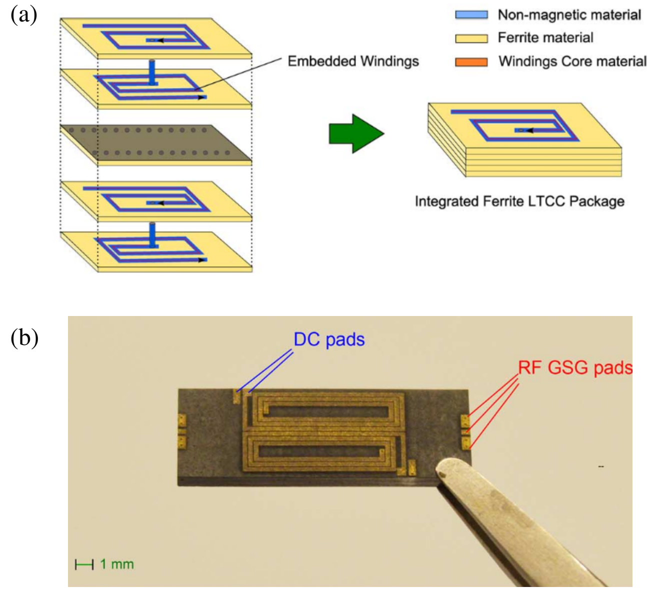

FIGURE 8. A typical ferrite phase shifter [38]. (a) The design of a substrate integrated waveguide (SIW) phase shifter with embedded bias windings in ferrite low-temperature co-fired ceramic (LTCC). (b) Phase shifter prototype that was manufactured.

a phase difference. As a result, phase shift values are typically preset and restricted to particular increments in phase shifter units that only use PIN diodes for control [45]. Researchers used a phase shifter that included several connected reconfigurable defective microstrip structures (DMS) units in a prior study [46]. These units were made by inserting a slot into a microstrip line and using PIN diodes to connect it. The DMS units were able to alter the current paths and create the required phase shifts by manipulating the PIN diodes and switching between the "ON" and "OFF" states.

    - In contrast to phase shifters controlled by PIN diodes, which have discrete and fixed phase shift values, varactor diodes allow phase shifters to continuously adjust the phase shift by adjusting the capacitance. The varactor diode-based coupled line construction is an example of a miniature analog phase shifter that was used to achieve a continuous transmission phase ranging from 0° to 180° [40]. It was made up of two identically lengthened parallel coupling lines that were connected at one end and loaded with a short-circuited stub and a varactor diode. There were two varactor diodes connected in series. When tested to maintain an IL between 0.95 and 1.35 dB at 5.6 GHz, this phase shifter continuously produced less.

    - High power levels are achievable due to tunable inductor-based phase shifters. These phase shifters have minimal IL, strong linearity, and a wide phase adjustment range. Additionally, they offer more consistent performance over temperature changes than

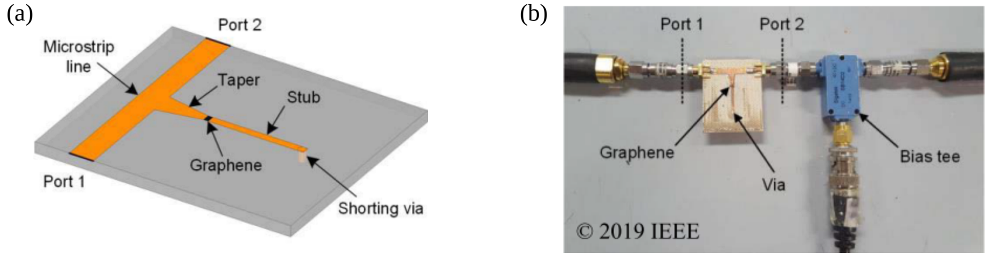

FIGURE 9. A typical graphene-based phase shifter. (a) The graphene-based phase shifter's geometry. (b) The measurement setup and the graphene-based phase shifter prototype.

TABLE 1. Comparative analysis of active and passive phase shifters.

Type	Benefits	Limits	References
Active phase shifters	- Lower insertion losses - Simple architecture - Compact geometry - Low cost for silicon surface area	- Higher DC consumption - Degraded linearity - Limited transmission power	[5, 48]
Passive phase shifters	- Reduces DC consumption - Improves linearity	- Less compact circuits - Higher insertion losses	

other options because they are less affected by temperature fluctuations.

- High linearity, wide bandwidth, quick switching speed, low IL, and high power handling capabilities are some of the benefits of RF MEMS switches. PIN diodes, FETs, and complementary metal-organic semiconductor (CMOS) transistors are all frequently replaced by MEMS switches [45].

3. **An additional category of analog phase shifters:** Analog phase shifters can also use novel materials like graphene [46] or $Ba_{0.7}$ $Sr_{0.3}$ TiO_3 [40]. In [47], a graphene-based phase shifter achieved a maximum phase shift of 40° within the 5 to 6 GHz range, with an insertion loss of 3 dB (see Figure 9). Because of the non-toxicity of gallium-based liquid metals such as Galinstan® and EGaIn, there has been a renaissance of research into liquid metal applications, particularly in the last 10–15 years. Some of the applications pursued by researchers (as outlined in the literature review) include reconfigurable antennas, stretchy antennas, strain, pressure sensors, and more [47].

In summary, several variables, including frequency range, intended phase resolution, IL level, power consumption, and geometric dimensions, influence the phase shifter implementation strategy. Every design approach has unique advantages and disadvantages in terms of manufacturing complexity, performance, size, and power consumption. Additional details and a comparison of various phase shifters will be provided in the section that follows.

3. COMPARATIVE STUDIES

Phase shifters are divided into two categories in the literature: active and passive. Table 1 provides a summary of both the benefits and drawbacks. The use of passive phase shifters is often restricted to Ku-band and lower due to several drawbacks, such as high IL, large size, and narrow bandwidth [49]. Active phase shifters, on the other hand, solve these problems by offering a smaller chip area and a larger gain. Table 2 compares various design topologies currently used to implement phase shifters, with summarized specifications and performance.

A summary of the performance of different electronic phase shifters is shown in Table 3 [47]. Compared to active phase shifters, passive ones, mainly STPS, RTPS, and LLPS, are more linear, have a greater power handling capacity, and consume less power. However, VSPS offer a smaller chip area, higher gain, and a relatively larger bandwidth than passive phase shifters. The majority of passive and active electronic phase shifters, except STPS, which is a digital phase shifter, can be configured to offer either continuous or discrete resolution. The MEMS solution has been the subject of a lot of recent research in an attempt to attain respectable performance in terms of power capability, bandwidth, IL, and chip area.

Table 4 shows the benefits and limitations of each type of phase shifter.

[2]Insertion Loss
[3]Return Loss
[4]Single-Unit Two-Bit Reflection-Type Phase Shifters
[5]Switched-Type Phase Shifters
[6]Reflective-Type Phase Shifters
[7]Loaded-Transmission Line Phase Shifters
[8]Vector-Sum Phase Shifters

TABLE 2. Comparison between different phase shifter topologies from the literature.

Reference	Type	Control	Frequency (GHz)	IL[2] (dB)	RL[3] (dB)	$\Delta\varphi(°)$
[50]	Switched line	Digital	13–18	2.7	22	349.3
[51]	Reflection type	Analogue	2	1	13.4	385
[52]	Network type	Digital	0.5–1	2.5	13	360
[2]	Loaded transmission line	Analogue	1	2	15	183
[53]	GFET CS Amplifier	Digital	3	–2.5	0.9	197.9
[53]	GFET CS Amplifier	Analogue	3	0	0.4	84.5
[29]	RTPS	Digital	1.37–1.43	2.3	> 15	180
[54]	Schiffman	Digital	1.5–6	1.2	> 10	323
[55]	Inverted-E	Digital	0.4–4	0.46–1.8	> 12–> 15	100
[56]	SUTBRTPSs[4]/single-unit	–	0.9–1.1	2.1	> 19	180

TABLE 3. Comparison of electronic phase shifters.

Performance	STPS[5]	RTPS[6]	LLPS[7]	VSPS[8]
Bandwidth	Narrow	Narrow	Narrow	Wide
Passive/Active	Passive	Passive	Passive	Active
Phase control	Digital	Digital/Analog	Digital/Analog	Digital/Analog
Power consumption	Low	Low	Low	High
Chip area	Large	Large	Large	Small
Linearity	High	High	High	Limited
Output power	High	High	High	Low to medium
Insertion loss	High	High	High	Low
Return loss	Medium	High	Low	High

TABLE 4. Comparative analysis of main phase shifter types.

Type	Benefits	Limits	References
Ferrite	- High power - Excellent reliability, radiation tolerant - Suitable for high-power applications	- Low integrability - Slow response (long tuning time) - Expensive, not suited for mass production - Significant power consumption	[50, 51, 56]
p-i-n diodes/Varactors	- Continuous tunability - Good isolation and reflection - Simple, low-cost, easy to manufacture	- Limited phase-shift resolution - High loss at mm-wave bands	[53, 54]
MEMS	- Very low insertion loss - High linearity over a wide bandwidth - Lower power consumption than semiconductors	- Reliability issues - Limited maximum operating frequency	[55, 56]
Tunable dielectrics	- Easy control and implementation - High tunability and resolution - Nearly linear phase tuning	- Complex configurations - Expensive - High power consumption	[54, 55]
Liquid crystal (LC)	- Low insertion loss at high frequency - Wide tuning range - High phase resolution	- Limited phase range in some designs - Slower switching speed than semiconductors	[57, 58]

TABLE 5. Comparative properties of liquid metals.

Property	Mercury	Gallium	EGaIn (Ga 75%, In 25%)	Galinstan®	Generic galinstan (Ga 68.5%, In 21.5%, Sn 10%)
Color	Silver [61]	Silver [62]	Silver	Silver [63]	Silver
Odor	Odorless [64]	Odorless	Odorless	Odorless [62]	Odorless
Toxicity	Hight	Low	Low	Low	Low
Boiling point	356.73°C [36, 61]	2204°C [63]	Estimated similar to Galinstan®	> 1300°C [63]	Similar to Galinstan®
Melting point	−38.83°C [61, 63]	29.76°C [62, 65, 66]	∼ 15.5°C [65]	−19°C [63, 67]	11°C [60, 68]
Density	13.534 g/cm^3 [61]	5.904 g/cm^3 [62]	6.2275 g/cm^3 [69]	6.44 g/cm^3 [63]	6.44 g/cm^3 [60, 62]
Solubility	Insoluble [64]	Insoluble	Insoluble	Insoluble [62]	Insoluble
Viscosity	1.526×10^{-3} Pa · s @ 25°C [60]	1.921×10^{-3} Pa · s @ 50°C [60]	1.99×10^{-3} Pa · s [69]	2.4×10^{-3} Pa · s [59]	$\sim 2.25 \times 10^{-3}$ Pa · S @ 25°C [70]
Thermal conductivity	8.541 W/(m · K) [60] 8.3 W/(m · K) [61]	29 W/(m · K) [62]	26.43 W/(m · K) [70]	16.5 W/(m · K) [59]	∼ 25.41 W/(m · K) [62]
Electrical conductivity	1.04 × 106 S/m [61]	7.1 × 106 S/m [62]	3.46 × 106 S/m [67] 3.4 × 106 S/m [59]	2.299 × 106 S/m [59] 3.83 ± 0.16 × 106 S/m @ 3–20 GHz	3.46 × 106 S/m [64]
Surface tension	> 0.4 N/m [67]	> 0.5 N/m [15]	> 0.5 N/m [15] ∼ 0.624 N/m [66] ∼ 0.435 N/m w/HCl [67]	> 0.5 N/m [15] 534 ± 10.7 mN/m [15]	0.718 N/m @ 20°C [62]

Mercury and other liquid metals have been around since 1500 BC [47], but gallium and its alloys were not found to be mercury substitutes until the 19th century. The characteristics of liquid metals based on gallium and mercury are summarized.

- **Mercury:** Mercury has been discovered in Egyptian tombs dating back to 1500 BC [58], Mexican pyramids from 1800 years ago, and ancient Chinese and Tibetan histories [47]. While it is impossible to identify exactly what it was used for back then, it has modern applications in dentistry, lighting, gauges, mining, and electronics, to mention a few.
- **Gallium:** Gallium is not a liquid metal at ambient temperature, like mercury, but its melting point is low enough (29.76°C [85.58°F]) to melt in a human hand and refreeze when removed [59]. When combined with other metals, some gallium alloys can have melting points as low as −19°C (−2°F) [59]. Since its discovery in 1875, gallium arsenide (GaAs) and gallium nitride (GaN) have been widely employed in electronics, particularly semiconductors. However, due to their non-toxicity, gallium liquid metal alloys have lately been employed as a replacement metal for a variety of mercury applications, including the thermometer [60].

Table 5 compares the properties of gallium, EGaIn, Galinstan®, and generic Galinstan, which includes mercury.

A thorough evaluation of the liquid metal (LM) phase shifter's performance in comparison to numerous cutting-edge LM phase shifters and other technologies operating at a frequency of 10 GHz is provided in Table 6. The recommended LM phase shifters in [58] offer low IL and RMS amplitude changes (< 1.5 dB in all states). The suggested phase shifters have a lower IL than any other cutting-edge phase shifters that allow for a 360° phase shift. At 10 GHz, the proposed phase shifters offer remarkable FoM performance of 131.3 and 122.4°/dB. Regardless of the technology being used, this FoM is significantly higher than all state-of-the-art phase shifters. Additionally, the suggested phase shifters are powered by SMA connectors and constructed using SIW technology. High levels of RF power can be handled by the suggested phase shifters. In all states, the LM phase shifters' proposed work cite alkaraki202310 achieves low IL and RMS amplitude changes (< 1.5 dB). With a 360° phase shift, the suggested phase shifters outperform all state-of-the-art phase shifters in terms of IL performance. Phase shifters can achieve impressive FoM performance of 131.3°/dB and 122.4°/dB at 10 GHz thanks to liquid metal technologies. Regardless of the technology used, this FoM is significantly higher (i.e., superior) than all state-of-the-art phase shifters. Additionally, the suggested phase shifters are fed via SMA connectors and constructed using SIW technology. High levels of RF power can be handled by the suggested phase shifters. Furthermore,

TABLE 6. Comparison of different phase shifter technologies.

Reference	Technology	Freq. (GHz)	IL (dB)	Phase shift (°)	BW (GHz)	FoM	RL (dB)	Size (mm^2)
[71]	Liquid Metal	367.6	< 2.8	13.3	≈ 45	20	< 1.5	57.2×14
[72]	Liquid Metal	180	2.3	78.3	10	10	NA	87.2×56.2
[73]	Liquid Metal (Non-uniform)	367.6	< 2.8	131.3	≈ 45	20	< 1.5	57.2×14
[73]	Liquid Metal (Uniform)	379.5	< 3.1	122.4	≈ 45	20	< 1.5	57.2×14
[74]	Ferroelectric based	413	10.3	40.1	NA	NA	> 3	3.8×2.3
[75]	Ferrite-LTCCC	215	< 7	48	NA	NA	NA	$\approx 45 \times 45$
[76]	Liquid Crystal	≈ 60	2.5	24	NA	NA	NA	NA
[77]	Liquid Crystal	≈ 101	≈ 5	15.2	NA	NA	NA	NA
[78]	Liquid Crystal	461	4.35	105.9	NA	NA	NA	NA
[79]	GaN	180	14	12.8	11.25	4.5	≈ 0.6	4.7×5
[80]	0.25 µm SiGe BiCMOS	360	< 12	< 30	11.25	6.4	> 3.0	1.87×0.88
[81]	0.13 µm CMOS	360	-	27.3	5.625	4.1	≈ 0.8	2.06×0.58
[82]	0.18 µm SiGe BiCMOS	360	11.9	30.25	5.625	4.6	≈ 0.6	NA
[83]	0.25 µm SiGe BiCMOS	360	≈ 13	27.7	5.625	4	≈ 0.6	3.42×0.95
[83]	PIN Diode-SIW	< 180	≈ 2	≈ 90	NA	NA	> 0.8	NA

high linearity can be attained because no active components are needed.

4. APPLICATIONS

One of the most important devices in the fabrication of reconfigurable PICs is the phase shifter. Several high-performance reconfigurable devices based on phase shifters have been proposed, including optical filters [84, 85], modulators [35, 86], and tunable delay lines [87]. On-chip spectrometers, photonic accelerators, optical phased arrays, and large-scale neuromorphic computing systems are all made possible by effective phase shifters with high modulation speed and low power consumption. The following systems' primary reconfigurability technology, according to the literature, is phase shifters:

- **Advanced optical computing systems**: In the post-Moore era, conventional computers based on the von Neumann architecture — which physically separates the processing module from the storage module — are running into speed and integration density constraints. Many scientists began looking at the next generation of computer architectures and offered numerous interesting computing platforms in an attempt to get over the limitations of Moore's Law. There are two kinds of:
  - **Neuromorphic Computing System**
  - **Photonic Accelerator**
- **Optical phased array**: Over the past 20 years, the optical phased array has advanced quickly, influenced by array radars in electronics. Due to its accurate and adjustable steering angle of emitted light, OPAs have emerged as a strong contender for spatially resolved optical sensors, LiDAR mapping, and optical communication in free space. Typically, an incident light coupler, a phase shifter array, and grating emitters make up an OPA.
- **Multi-functional signal processing systems**: In electronics, Perez et al. suggested a hexagonal mesh structure that was influenced by FPGAs [88]. Ring-loaded MZIs, optical ring resonators, coupler resonator waveguides, side-coupler integrated spaced sequences of optical resonators, and single-input/single-output FIR filters are just a few of the many functions made possible by this structure's phase shifters on either side of the hexagon. The photonic integrated circuits' functionality and scalability are significantly enhanced by the architectures.
- **On-chip spectrometer**: In laboratories and industry today, spectrometers are crucial instruments for calibration and measurement. Spectrometers are currently trending towards downsizing, and researchers have made significant efforts in this respect, even though bulky, contemporary spectrometers are capable of high-resolution observations [89, 90]. The spectrometer application may be made possible by the integrated phase shifters' on-chip light splitting and routing capabilities, which produce on-chip light interference.

5. CHALLENGES AND FUTURE TRENDS OF PHASE SHIFTERS FOR PHASED ARRAY SYSTEMS

5.1. Liquid Metal-based Phase Shifters

Since they allow for more flexible tunable systems, liquid metals have been used to create reconfigurable components such as filters [90], sensors [91], frequency-selective surfaces [92], and antennas [93]. We have already covered a number of phase shifter types in the comparative study section. Phase shifters and reconfigurable liquid metal surfaces are the particular topics of this section. The focus of our study is on recognizing, resolving, and enhancing the problems related to this kind. Additionally, Table 7 will be presented, which lists various liquid

TABLE 7. Comparative analysis of Liquid Metal phase shifters.

Ref.	Liquid Metal	Benefits	Limits
[66]	Galinstan	- Enable reversibility and reconfigurability - Wide operating frequency range - Flexibility - Efficient performance	- Limitation in frequency range - Nonlinearity
[89]	Galinstan R and EGaIn	- Stretchability - Safe handling and operation - High performance	- High weight and sagging - Air gaps - Fabrication complexity
[72, 94]	Gallium	- Reconfigurability combining planar antennas, mmWave, and IoT - Wide phase shift range - Low insertion loss	- Reconfiguration speed - Fabrication complexity - Reliability issues - Performance restrictions
[66, 89]	Gallium	- Easy reconfigurability - Wide phase shifting range - Low insertion loss - Compact design	- Performance impact - Corrosion and oxidation - Higher cost than solid-state materials
[68, 69]	Gallium	- Wide phase shift range (0°—360°) - Operation at 10 GHz with low losses - Exceptionally low insertion loss - Compact footprint	- Gap between measured and simulated results - SIW integration challenges (reliability, longevity) - Need for optimization
[72]	Galinstan/EGaIn	- Large phase tuning ratio - Low insertion loss - Compact design - High power handling	- Impact on RF performance - Size considerations - Fabrication difficulties - Integrity maintenance

metal-based phase shifters along with their drawbacks based on current research findings.

Table 7, shows the difficulties associated with each liquid metal-based phase shifter. Subsequent research could use this information as a foundation to enhance and progress the liquid metal phase shifter. Making the phase shifter smaller in size could expand its potential applications. Additionally, a smaller phase shifter would be more manageable and flexible during the phase shift calibration process. Further enhancements to the phase shifter could involve refining the structure for dispensing liquid metal. Moreover, future investigations could explore alternative designs, such as a flat phase shifter, which might be more suitable for confined spaces.

5.2. Future Trends of Phase Shifters for Phased Arrays and Emerging Applications

Phased array antenna techniques continue to be the most popular beam-steering methods because of their special advantages, which include excellent SNR/SIR, broad coverage, and quick scanning. This is particularly relevant given the development of 5G and other communication networks. To accommodate the bandwidth requirements of billions of linked devices, current 5G wireless systems are expected to continue using mm-wave bands, which can deliver up to 10 GB/S of data throughput with 1 ms latency [60, 95]. Meanwhile, as mentioned before, phase shifters largely determine the cost and performance of phased array systems. Since precise and low-loss phase shifters are frequently implemented through expensive process technology, future research on electronic phase shifters aims to develop phase shifters with respectable performance at mm-wave frequencies using cost-effective techniques. The most popular phase shifter type for silicon technology is still active phase shifters because of their gain and small size. However, the poor phase resolution of active phase shifters resulting from phase gaps and relatively high power consumption will need to be addressed in future research. Additionally, MEMS technology is a popular alternative to CMOS technology for constructing low-loss phase shifters. Finally, there is increasing interest in using liquid metal (LM) to create phase shifters with large phase ranges and minimal loss [6, 60, 96]. Similar to the LC device, LM-based phase shifters are very new and hence need further investigation, particularly at mmwave frequencies where LMs have difficulties with confinement and correct actuation [60]. The design of low-cost and low-loss beamforming and power-feeding networks is also necessary for the phase shifters to lower the overall system cost, even though improving and making electronic phase shifters more cost-effective is still necessary. Although electronic phase shifters need to be improved and made more cost-effective, the phase shifters also need to be designed with low-cost, low-loss beamforming and power-feeding networks in order to lower the entire cost of the system. Due to its affordability and compact size, the Butler matrix (BM) beamforming network has attracted a lot of interest [60]. However, mm-wave BM structures require very small transmission lines, posing fabrication challenges. Therefore, in order to get over this restriction, future research on BM feeding networks will involve creating strategies such as using metamaterials. But the mm-wave BM structures need extremely tiny lines, which are hard to make. As a result, future research on BM feeding networks will focus on creating strategies like using metamaterials to get around this restriction. Finally, feeding networks, including coherently radiating periodic structures, are being investigated to provide a reasonable scanning angle while lowering the system cost by reducing the overall number of phase shifters [97]. These methods, however, are still in their infancy and primarily cover frequencies below 10 GHz with a narrow range of beam angles. To create novel beamforming networks with fewer phase shifters at mm-wave frequencies, more research is required.

In addition to phased array antennas, phase shifters are becoming more and more popular in several other application areas. They play a crucial role in reconfigurable intelligent surfaces (RIS), which manipulate wavefronts to enhance spectral efficiency and coverage in next-generation wireless systems [98]. Phase shifters reduce payload weight and complexity while enabling adaptive beam steering in satellite and space communications. In radar and sensor systems, where accurate phase control enhances imaging resolution and detection accuracy, it is equally crucial [99]. Additionally, phase shifters are being investigated for adjustable modulators and small interconnects at optical and terahertz frequencies [84, 100]. In biomedical applications, which are expanding beyond traditional engineering fields, phase shifters allow for promising methods for noninvasive imaging, diagnostics, and maybe therapeutic systems [88, 101]. When combined, these varied advancements high-light how phase shifters will play a significant role in enabling wireless, photonic, sensing, and medicinal technologies in the future, going far beyond phased array antennas.

6. CONCLUSIONS

Phase shifters are thoroughly examined in this comprehensive review. It talks about the field's future directions and compares performance. Transmission line phase shifters, ferrite phase shifters, hybrid coupler phase shifters, semiconductor phase shifters, digital phase shifters, and reflective load phase shifters (RTPS) are some of the important technologies that have been discussed. Additionally, a novel liquid metal-based phase shifter technology was covered. Future studies are supposed to concentrate on developing and refining liquid metal phase shifters, possibly by making them smaller in order to expand their possible uses. Additionally, it would be simpler to manage and modify a smaller phase shifter when adjusting the phase shift. The review highlights the significance of evaluating a variety of performance indicators. For engineers and researchers working on the design of liquid metal phase shifters for a range of applications, it is an invaluable resource. It also identifies important obstacles and potential paths forward in this area. Therefore, future research will focus on developing suitable feeding networks that call for simpler fabrication processes and deploying phase shifters with low phase errors and loss using economical technologies in order to reduce the overall cost of phased array systems for wireless 5G/6G communication systems.

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