Review

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Posted Date: 19 November 2024

doi: 10.20944/preprints202411.1386.v1

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*Review*

# A Comprehensive Review on Phase Shifters:Topologies, Types, Comparative Studies, Liquid Metal Phase Shifters, and Future Directions

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**Abstract:** RF signals are widely used in various applications such as telecommunications, wireless communication systems, and radar systems. These signals can be manipulated using phase shifters that adjust the the signal's phase. This adjustment is essential for beam shaping, signal cancellation, and frequency synthesis in antenna arrays. By controlling phase of the RF signal, phase shifters help manipulate electromagnetic waves for various applications. Therefore, as Gallo points out, phase shifters are essential for manipulating and controlling high-frequency signals. This manipulation and control is essential to improving the performance of wireless communication and radar systems and can improve signal reception and transmission.The study examines different types of phase shifters, conducts a comparative analysis of different phase shifter topologies and technologies, and highlights their respective advantages and limitations in applications. In addition, the review includes a specific study of liquid metal phase shifters. Finally, the article outlines future research directions for liquid metal phase shifters, It emphasizes the need for innovative design strategies to keep pace with the evolving wireless communications and telecommunications fields. Therefore, this article can serve as a reference for the milestones in RF phase shifter research.

**Keywords:** Antenna, Beamforming, Liquid metal phase shifters, Radio Frequency, Phase shifters.

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## 1. Introduction

Phase shifters are essential components in various microwave system designs and applications [1] such as phase modulators, harmonic distortion suppression, beamforming [2], etc. The most popular application of phase shifters is beamforming using antenna arrays in phased array platforms. Beamforming is very important for improving 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, a major drawback of digital beamforming techniques is the high cost, increased system complexity, and loss of applications such as the massive MIMO with a large number of antennas [4]. However, the main distinction is between 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 needed to change the phase shift set point using, for example, MOSFET transistors. But 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, noise figure (NF), and large on-chip space requirements.

On the other hand, active phase shifters decrease linearity but increase compactness, minimize losses (and possibly even increase gains), and adjust gains. This reduces the workload for the VGPA in correcting signal losses and padding the data. [5].

Phase shifters need to be small in size, inexpensive, and have little insertion loss within the intended bandwidth. Due to space limits, phase shifter size is an important element, particularly in the design of portable microwave devices. However, the development of high-resolution RF phase shifters accounts for about 50 % of the total system cost and remains a challenge in realizing compact phased array beamformers [6]. Since the performance of a phase shifter mainly depends on its technology, this paper studies various topologies/types of phase shifters based on their phase tuning mechanisms and techniques, focusing on their advantages/limitations and the state-of-the-art techniques to overcome their disadvantages also focus in the liquid metal phase shifters.

## 2. Methodology

This section focuses on the experimental characterization of phase shifts and the principles of phase shifters. Further details are explained below:

### 2.1. Phase Shift's Experimental Characterization

To determine the phase shift, you can place the shifter in an unbalanced Mach-Zehnder Interferometer (MZI) or ring resonator. The phase shift value can be obtained from the MZI optical transmission spectrum by applying DC voltages with different amplitudes [7]:

$$\Delta\varphi = \frac{|\lambda(V_0) - \lambda(V)|}{FSR} \tag{1}$$

where $\lambda\ (V_0)$ is one of the MZI spectrum drop wavelengths in the initial state without applied voltage, $\lambda(V)$ is the same MZI spectrum drop wavelength as the applied voltage, and FSR is the free spectral range of the MZI spectrum. The unit of $\Delta\varphi$ is 2 $\pi$.

The $n_{eff}$ can be determined by tuning the resonance wavelength of a ring resonator [8] :

$$\Delta n_e f f = \frac{\Delta\lambda_{ress}.m}{L}, m = 1, 2, 3... \tag{2}$$

where $\Delta\lambda_{ress}$ is the resonance wavelength tuning and L is the round-trip length.

### 2.2. The principle of phase shift

A PAS's fundamental component is an RF phase shifter. Through a control element, it is used to alter the input signal's transmission phase. This can be accomplished either actively or passively. Thus, both active and passive phase shifters are available. Phase shifters are employed in many different applications outside PASs, such as image rejection receivers [9], linearization of amplifiers [10], and electrical testing devices like signal generators [11]. Changing the phase of an incoming signal without altering other parameters like 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:

$$S = \begin{bmatrix} 0 & e^{j\varphi} \\ e^{j\varphi} & 0 \end{bmatrix} \tag{3}$$

Even though ideal phase shifters only change the signal phase, as demonstrated by equation 3, practical RF phase shifters suffer from performance degradation. Several parameters can determine the performance of an RF phase shifter, including the frequency capability/bandwidth, insertion loss, return loss, linearity, power handling, phase range/resolution, phase error, chip area, and power consumption .

#### 2.2.1. Frequency Capability and Bandwidth

The bandwidth of RF phase shifters should be $BW = f_H - f_L$, where $f_H$ and $f_L$ are the upper and lower cutoff frequencies, respectively, and they should function at a center frequency ($f_0$). A common

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name for the bandwidth is the 3-dB bandwidth. The frequency range where the reflection coefficients (S11,S22) are less than -10 dB; however, maybe referred to as the bandwidth of viable RF phase shifters. The percentage of the bandwidth with regard to the center frequency is known as fractional bandwidth (FBW), and it is commonly expressed as $FBW = \frac{f_0}{BW} * 100$. Operating at high frequencies with the phase shifter frequently desires a wide bandwidth. However, because of the decline in the quality factor and performance of passive and active parts at higher gigahertz frequencies, designing high frequency and big bandwidth phase shifters is difficult [12].

#### 2.2.2. Insertion and Return Losses

The insertion loss (IL), which is equal to the negative of $S_{21}$ in decibels (dB), is the energy loss of the transmission mode RF phase shifter when the signal moves from the input to the output $(IL = -20 \log |S_{21}|$ Moreover, it indicates the gain of the phase shifter. Gain imbalance is the phrase used to describe the variance in gain over the bandwidth, which ought to be as small as feasible. Compared to their active counterparts, passive phase shifters result in higher insertion loss. Additionally, an RF phase shifter's insertion loss usually rises with frequency. In contrast, the energy loss resulting from an incoming signal being reflected at the device's input or output is measured by the return loss (RL). $S_{11}(RL_{in} = -20 \log |S_{11}|)$ measures the input return loss, whereas $S_{22}(RL_{out} = -20 \log |S_{22}|)$ measures the output return loss. Low insertion loss and high return loss are requirements for phase shifters.

#### 2.2.3. Linearity

Linearity serves as a crucial parameter in the design of RF phase shifters. To prevent intermodulation effects and subsequent challenges in signal demodulation on the receiver 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 [12].

#### 2.2.4. Resolution and Phase Range

According to Equation 4, the phase range is the phase difference between the reference phase $(\varphi_{ref})$ and the greatest achievable phase shift $(\varphi_{max})$ [6]:

$$\varphi_{range} = \varphi_{max} - \varphi_{ref} \tag{4}$$

The reference value can be subtracted from the actual phase shift to normalize the phase state $\varphi$ :

$$\Phi = \varphi - \varphi_{ref} \tag{5}$$

In this context, the phase shifter's reference value is set to 0°, and the phase range $(\varphi = \phi_{max})$ determines the maximum normalized phase shift. A phase shifter's resolution 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 depends on the number of bits N of the bit control or DAC [6]:

$$\varphi_{resol} = \frac{\Phi_{max}}{2^N} \tag{6}$$

With a 2-bit phase shifter, the resolution is resol $\Phi_{resol} = 90$, and the potential phase states are $\Phi_1 = 90, \Phi_2 = 180, \Phi_3 = 270, and \Phi_4 = 360$. The phase range max is 360°. The number of control bits is occasionally used to express the resolution. The resolution of many useful digital phase shifters can

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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 [13] .

#### 2.2.5. Power Handling

For phase shifters, power handling is an essential parameter, 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 harm or appreciable performance deterioration.Due to transistors' limited P 1dB, passive phase shifters are better at handling power than active phase shifters [6].

#### 2.2.6. Amplitude and Phase Errors

The difference between the desired and measured actual phase shifts is known as the RF phase shifter's phase error. This is how it is expressed [14]:

$$\epsilon_{\varphi} = \Phi - \Phi_0 \tag{7}$$

where the measured and desired phase states are denoted by $\Phi$ and $\Phi_0$, respectively. The accuracy of the phase shifter is frequently assessed using the root mean square (RMS) phase error. The RMS of the actual phase faults at every potential phase shift is used to obtain it.

#### 2.2.7. Surface area

Phase shifter size is a crucial factor that needs to be kept within reasonable bounds. Due to the fact that RF phase shifters typically use inductors that take up a lot of space, they are frequently very big. Area consumption for passive phase shifters is primarily determined by frequency, process technology, and resolution/phase range. They show larger regions at lower operating frequencies and higher phase resolution [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].

#### 2.2.8. Power Consumption

Like other radio frequency modules, phase shifters should have low to no DC power consumption. However, a lot of active phase shifters conduct phase adjustment using VGAs, result in respectable DC power usage.Amplification is also necessary for certain phase shifters to increase the signal's strength and quality. Consequently, the amount of DC power used rises. In contrast, digital phase shifters usually use very little DC power because they mostly use passive components such capacitors and inductors, which don't need voltage consuming.

RF phase shifters are classified in a variety of ways. There are mechanical, ferromagnetic/magnetic, micro-electromechanical systems (MEMS), and electronic phase shifters that are based on the phase tuning mechanism. The components or building blocks of RF phase shifters are used to classify them as either passive or active. Additionally, depending on the control voltage, phase shifters can be either digital or analog, but this usually refers to electronic phase shifters [6]. The next section describes the types of phase shifters and their topologies.

## 3. Related Work

### *3.1. Phase Shifters - Definition*

We provide the following definition of phase shifters taken from literature:

- **Definition 1:**A phase shifter is a transformer-based device that regulates the phase angle of voltage in a power system. The phase shifter regulates power flow across a power line by shifting the phase of terminal voltage phases [15]. Phase shifters play a crucial role in microwave systems, including phase modulators, frequency up-converters, and phased arrays. They enable adaptive beam shaping and steering [16].
- **Definition 2:**. Phase shifters can be defined as two-port passive microwave devices that allows for the adjustable phase changing of the incoming RF signal at the output port. Both the input and output ports should have perfect impedance matching to result, ideally, attenuating the outgoing signal at zero. These approximations are realized by proper design criteria to obtain the best performance [17].
- **Definition 3:** Phase shifters are the major building blocks of "phase array antenna" systems. They are mostly employed in the back of transmitter antennas to electronically steer the antenna beams. Two-port lossless phase shifters are used. From input to output, they change the transmission phase. The transfer scattering parameter's phase $\phi_{21}$(w), describes the phase shift and is measured by [18]:

$$S_{21}(jw) = |S_{21}(jw)|e^{j\phi_{21}}(w)$$

- **Definition 4:**A phase shifter is a transformer-based device, of which the essential feature is to regulate a phase-angle of a voltage in a power system. Changing the phase shift between terminal voltage phasors, the phase shifter regulates power flow through a power line. This feature of the phase shifters may be used to overcome problems with loop flow in a power system. These undesirable power flows cause increasing power losses and by that reduce the transmission capability of power lines. The phase shifters redirect power flows in a power system, which can improve the stability of this system [19].

### *3.2. Phase shifters as key components in phased array systems*

Phase shifters, as a key component of phased array antenna systems, are of great significance for low-loss beam steering or scanning. In particular, phase shift and insertion loss need to balance the following performance specifications.

1. mmWave phase shift 0-360° or 0-180° without exceeding insertion loss limits .
2. The insertion loss variation over the entire phase shift range over the desired frequency band is small, i.e., h. The insertion loss variation with bias control is small. This is done to minimize beam distortion during steering. Since signal combining and nulling in undesirable directions are significantly affected by the signal amplitude in each channel, the phase shifter must not only have low insertion loss, but also maintain constant loss over its phase tuning range.
3. High phase shift resolution.
4. Control is facilitated by factors such as low frequency bias, along with a linear phase shift-voltage response and minimal power consumption, exemplified by a bias voltage of less than 10V.
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 inserted.

This low-loss, high-tuning-range phase shifter technology can be used in a phased array transceiver to provide certain functions, such as 5G mobile communications (57GHz-66GHz in Europe), satellite communications (60GHz), gesture sensing (60GHz), and automobile radar (76GHz-81GHz), among others. Out of all of these options [20].
The following Figure 1 shows the block diagram of the application of a phase shifter:

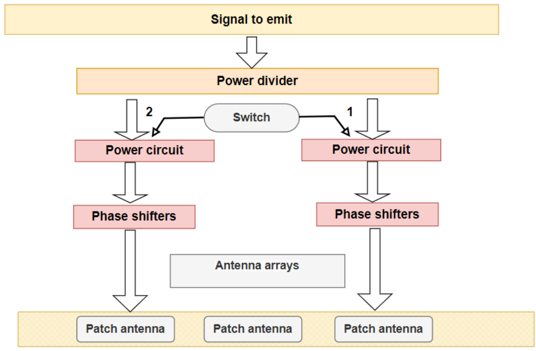


**Figure 1.** block diagram of the application of a phase shifter

### *3.3. Topologies of Phase Shifters*

As we noted in the first section, phase shifters play a crucial role in microwaves and millimeter wave systems by regulating the phase of a signal. The circuit configuration, or topology, of these components has a direct impact on their performance attributes, including phase shift range, bandwidth, and insertion loss. Below are several common topologies from the literature :

- 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 some of these. To begin, let's provide a brief definition of phase shifters based on various literature reviews.

### *3.4. Types of Phase Shifters*

Phase shifters can be divided into three main groups according to the method used to execute the phase-shifting functionality: digital phase shifters, optical phase shifters, and analog phase shifters.

#### 3.4.1. Digital phase shifters

Through the digital management of each phase-shifter bit, digital phase shifters enable the phase will discretized into predetermined phase states, enabling state switching. How many phase states the system can switch to depends on how many bits are included in the digital phase shifter. One of the most important aspects of digital phase shifters is their ability to accurately alter states. To implement digital phase shifters, various techniques have been used.

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 moveable in response to pressure, electrostatic, thermal, piezoelectric, or magnetic pressure. Electrostatic control is the most commonly utilized actuation method in microwave applications. Switches and radio frequency variable capacitors are the two main applications being pursued. Both of these devices operate on the same concept [19,21], and were applied to achieve the state switching of the phase shifter, as Figure 2 shows:

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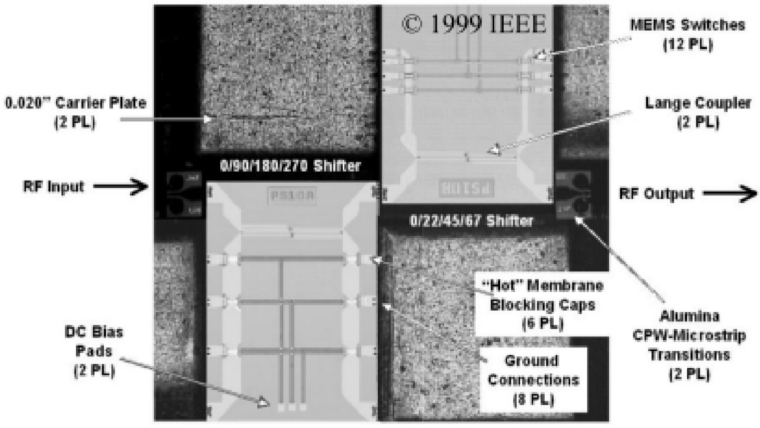


**Figure 2.** Photograph of assembled 4-bit MEMS phase shifter circuit [22]

There are numerous approaches(topologies) available for implementing RF MEMS digital phase shifters, as Figure 3 illustrates:

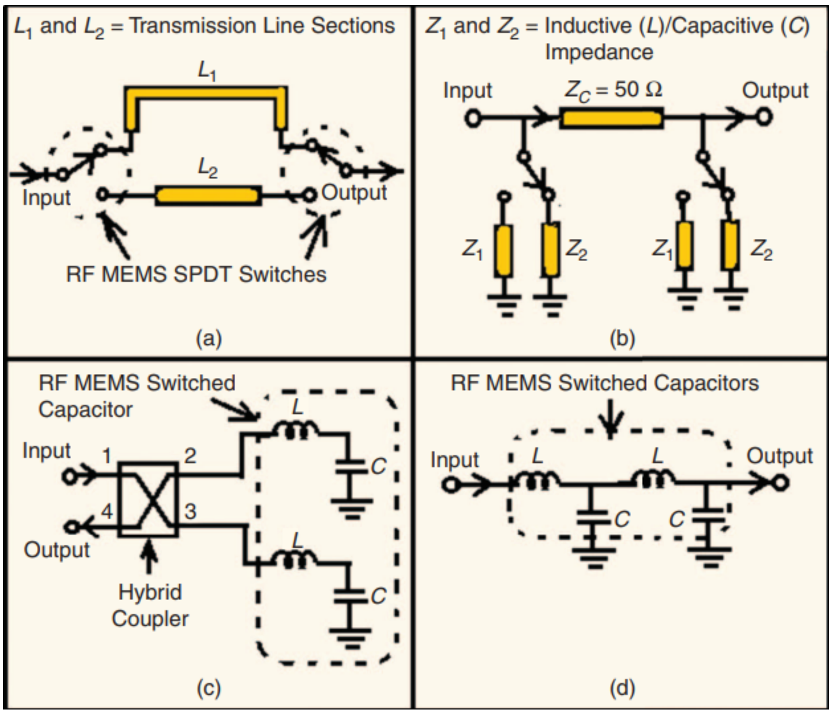


**Figure 3.** The schematic layouts of (a) switched-line, (b) loaded-line, (c) reflection, and (d) distributed-line RF MEMS phase shifter design implementations. SPDT: single-pole double-throw[17] .

- **Switched line phase shifters**: In terms of approach and design criteria, switching-line implementation is the simplest of all phase shifters. Their losses are comparable to the aggregate losses of switches and lines. This type of phase shifter can be built utilizing SPNTs (Single Pole N Throw) in either series or parallel mode. In Ka-band, 90° and 180° phase shifters with phase delay lines were constructed [23,24]. Figure 4 illustrates the simplest version of SLPS, which uses four Single Pole Single Throw (SPST) switches to transmit signals between two transmission lines of varying lengths. The equation 8 gives the differential phase shift between the two trajectories.

$$\Delta\Phi = \beta(L_2 - L_1) \tag{8}$$

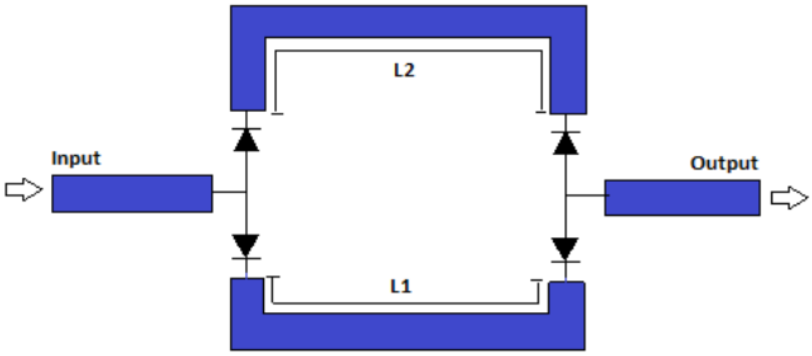


**Figure 4.** Basic schematic of a switched line phase shifter [23]

The schematic layout of a standard RF MEMS three-bit switched-line phase shifter with a MEMS series switch is shown in Figure 5, The sequence shows three separate sections (bits) that each produces phase shifts of 30°, 60°, and 120°, cascading linearly. Each section (bit) comprises a delay line (generating the required amount of 30°, 60°, or 120° phase shift) and the reference line (of 0° phase shift), with switching elements in both the delay and reference lines. This makes it possible to select each transmission line section separately to achieve a specified phase shift value at the output; for instance, to generate a 90° phase shift, To achieve a 180° phase shift, it is necessary to select the first and second bits, and the second and third bits are also necessary [17]:

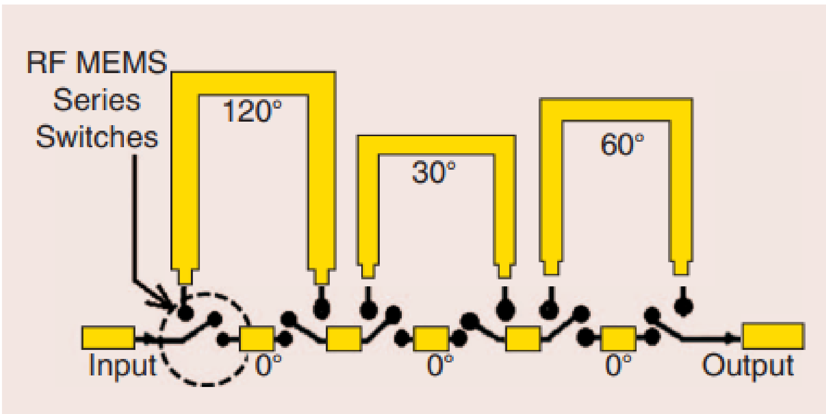


**Figure 5.** The schematic layout of the switched-line phase shifter [17]

- **Loaded line phase shifters**: The idea of loaded-line phase shifters dates back to the early 1960s and has been described in several research publications [25–27]. 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 plan is to load a line with two distinct impedances. A central line segment connecting the two networks may be utilized as a matching network to maintain input and output impedances close to 50 Ω, as shown in Figure 6.

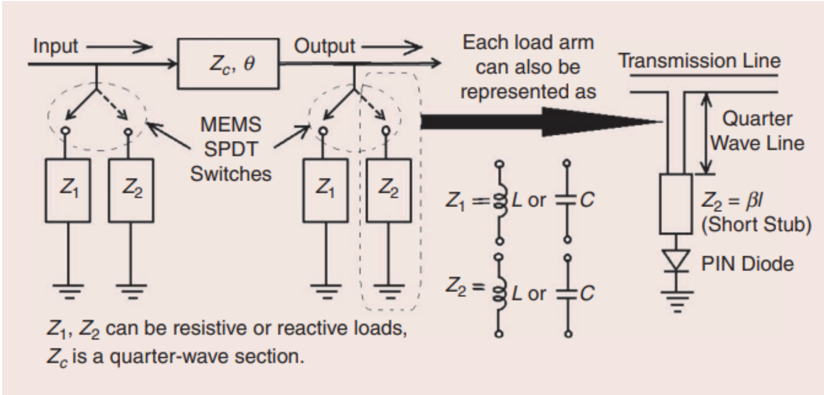


**Figure 6.** The basic schematic of the loaded-line phase shifter [25]

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 [25].

Figure 7 represents the simulation model for a switched line with a loaded line. The long path has two tuning stubs (equivalent to a loaded line) at each corner, and the short path has one in the middle. To adjust the phase shift, simply change the length of the stubs.

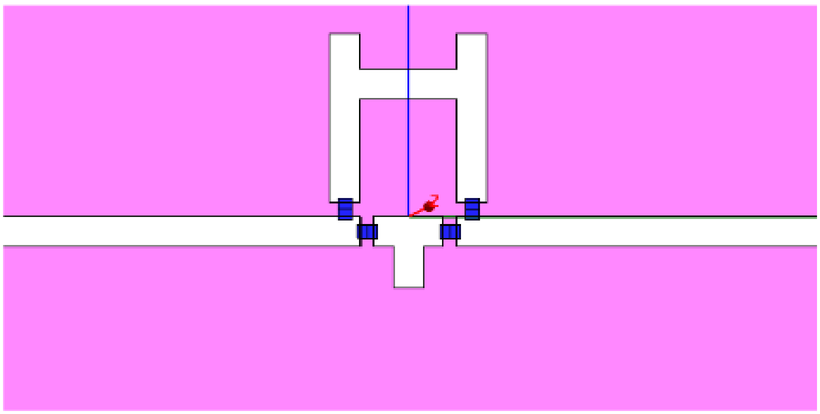

**Figure 7.** Simulation model of switched-line with loaded-line [25]

- **Reflection Phase Shifters**: Similar to the earlier examples, digital and analog versions of RF MEMS-based reflection-type phase shifters can be built; however, the analog format is not commonly employed due to its complex design. Reflection phase shifters employ 3-dB hybrid couplers as one of their main components, in contrast to the previously documented switched-line and loaded-line phase shifter implementations.

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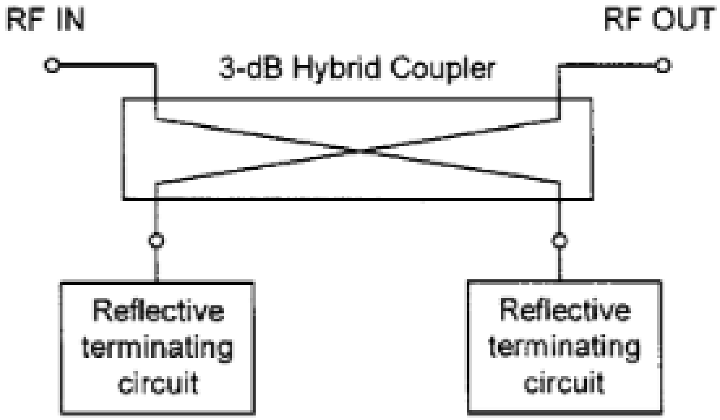


**Figure 8.** Schematic diagram of a reflection-type phase shifter [28]

Figure 9(a) and (b) demonstrate two distinct approaches for implementing the reflection-type N-bit phase shifter, both of which use a sequence (say, "N") of MEMS series or shunt switches on a transmission line.

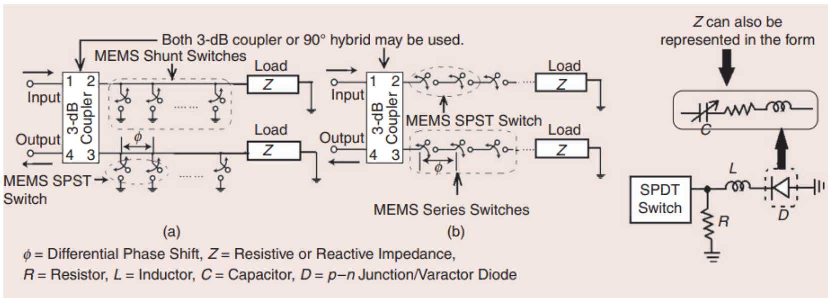


**Figure 9.** Schematic diagram of a reflection-type phase shifter [28]

- **Based Distributed-Line Phase Shifters**: The most popular among all RF MEMS-based phase shifters is distributed-line phase shifters, or rather, distributed MEMS transmission line (DMTL) phase shifters. This category encompasses the majority of studies that relate to MEMS-based phase shifter designs, and they are still in the process of being researched. The principle of their operation is that a transmission line, like a CPW or microstrip line, is loaded by passive components, like switched capacitors or varactors, periodically.

2. **Transistors**: In [29,30], transistors were used as switches, while resistors and capacitors were used to create the phase-shifting function. Compared to passive designs, active phase shifters [31], where differential phases are obtained by the roles of transistors rather than passive networks, can achieve a high integration level with decent gain and accuracy, as well as fine digital phase control under a constrained power budget.
3. **PIN diodes**: These are commonly used in digital phase shifters to control signal phase shift. To adjust the conductivity of a digital phase shifter, the PIN diode is biased in either the forward or reverse direction. When the PIN diode is forward-biased, it acts as a low-resistance switch and permits current to pass through it. When the diode is reverse-biased, it has a high impedance and functions as an open switch. Phase shifters make use of numerous PIN diodes to create discrete phase shifts. Each PIN diode has a unique control signal that affects its biasing status. The phase shift can be regulated in discrete stages by using enabled diodes. In the proposed design [32], as shown in Figure10, the PIN diode was 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.

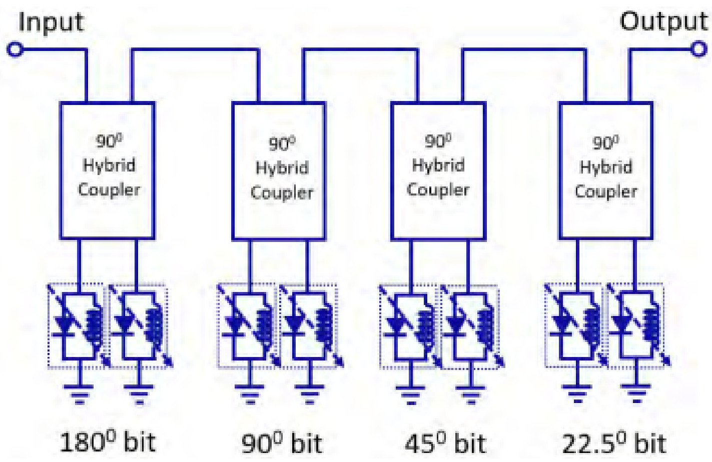


**Figure 10.** Configuration of 4-bit PIN diode reflection-type phase shifter [32]

3.4.2. Optical phase shifters

Optical phase shifters are crucial in a wide range of RF over-fiber applications. Microwave systems can benefit from the use of optical phase shifters, which include broad bandwidth, resistance to electromagnetic interference, superior isolation, and the ability to enable antenna remoting[33] [34]. Microwave e optical, such as optical delay lines, are utilized in the implementation of optical phase shifters [35]. Despite this, optical phase shifters require a significant number of optical switches, leading to a significant increase in terms of cost and complexity of the entire system [31]. To achieve integrated optical switches, several works have been suggested. Although electro-optic effects are the main modulation principles for the optical modulators [36], other principles, such as a thermo-optic effect [37] or MEMS actuators [38], are also widely used for optical switches to achieve high scalability and low crosstalk. In the case of the electro-optic optical and thermo-optic switches, an optical phase shifter is implanted into the interferometer or resonator structures as shown in Figure 11; thus, efficient modulation schemes discussed in previous captures are also partially effective for high-performance optical switches. On the other hand, the MEMS actuators of MEMS optical switches made by poly-Si or silicon-on-insulator (SOI) are mechanically moved to connect each optical pass.

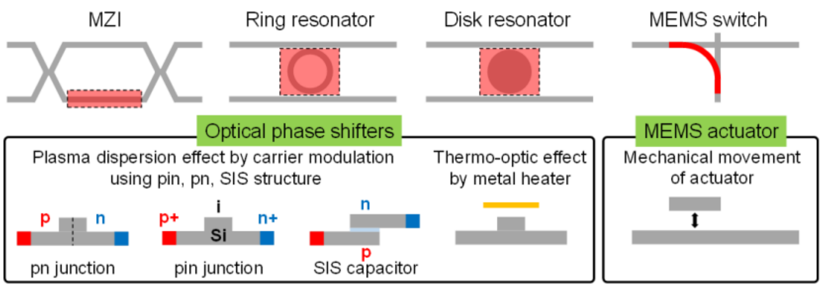


**Figure 11.** Schematics of various optical switches in large-scale Si PICs [39]

3.4.3. Analog phase shifters

Another significant type of phase shifter is analog phase shifters, which operate by altering the phase of an input signal through analog circuits. There are many different types of phase shifters covered by the concept.

1. **Ferrite phase shifters**: These traditional analog phase shifters use ferrite materials' magnetic characteristics to produce phase shifting. Ferrite phase shifters work on the Faraday effect and the interaction of a magnetic field with a microwave signal [40,41]. Ferrite phase shifters have been used in microwave power applications for over two decades, providing fine phase control

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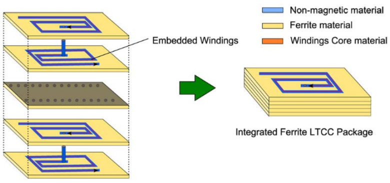
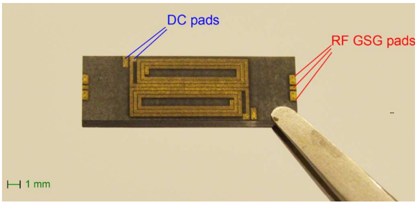
at moderate to high levels. However, this form of phase shifter is typically big and consumes a significant amount of power, making it unsuitable for compact and affordable microwave systems. Ferrite phase shifters have been used for over two decades in applications that require accurate phase control at moderate to high microwave power levels. However, this form of phase shifter is typically big and consumes a significant amount of power, making it unsuitable for compact and affordable microwave systems. Figure 12b represents a conventional ferrite phase shifter, as reported in [42].




(**a**) The structure of a phase shifter based on substrate integrated waveguide (SIW) in ferrite low-temperature co-fired ceramic (LTCC) with embedded bias windings




(**b**) fabricated prototype of the phase shifter

**Figure 12.** A typical ferrite phase shifter [42]

2. **Electronic components include phase shifters**: Phase shifters use solid-state electrical components to modulate signals and control the phase shift. They are less expensive to operate since they do not require costly digital gear in the network. As a result, a large amount of research and development has been focused on phase shifters to enable low-cost and downsized microwave systems [17]. The phase shift of electronic components, including PIN diodes [42] [17], varactors [43,44], tunable inductors, transistors, and MEMS devices, can be modified within a specific range by adjusting the voltage applied to them [44–48].

    - Typically, PIN diodes function as switches, maintaining two distinct states: 'ON' and 'OFF' , which create a phase difference. Consequently, in phase shifter units that solely utilize PIN diodes for control, the phase shift values are generally predetermined and limited to specific increments [49]. In a previous study [50], researchers utilized a phase shifter that incorporated a series of interconnected reconfigurable defected microstrip structure (DMS) units. These units were created by introducing a slot into a microstrip line and connecting it with PIN diodes. Through the manipulation of the PIN diodes, switching between the 'ON' and 'OFF' states, the DMS units were able to modify the current paths and produce desired phase shifts.
    - With varactor diodes, phase shifters can continually tune the phase shift by continuously adjusting the capacitance, in contrast to phase shifters controlled by PIN diodes that have discrete and fixed phase shift values. An example of a tiny analog phase shifter that was utilized to accomplish a continuous transmission phase ranging from 0°to 180° was a varactor diode-based coupled-line construction [44]. Figure 13 shows the structure of this tiny analog phase shifter. It was comprised of two parallel coupling lines of identical length, joined directly at one end and loaded with a varactor diode and a short-circuited stub. Two varactor diodes were connected in series between parallel coupled lines and grounded via a microstrip line and a via hole. This phase shifter was tested to keep its insertion loss between 0.95 and 1.35 dB at 5.6 GHz, and it consistently achieved less than 3 dB insertion loss between 5.35 and 6.32 GHz.

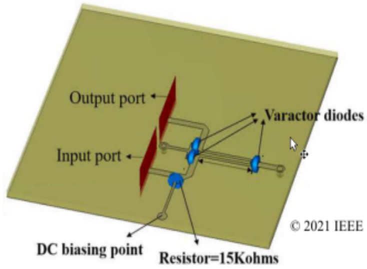
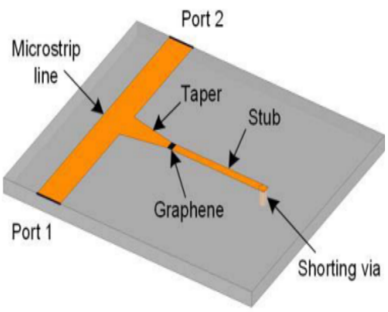


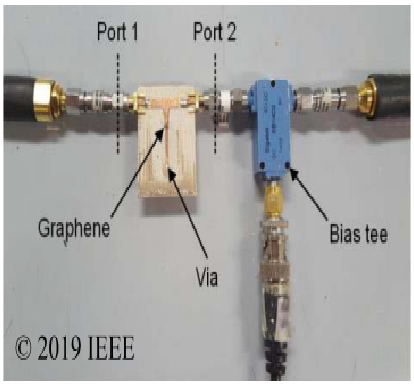

**Figure 13.** Schematic of a compact 180° analog phase shifter[49]

- High power levels are achievable thanks to tunable inductor-based phase shifters. These phase shifters have minimal insertion loss, strong linearity, and a wide phase adjustment range. Additionally, they offer more consistent performance over temperature changes than other options because they are less affected by temperature fluctuations.
- The advantages of RF MEMS switches, such as low insertion loss, high linearity, wide bandwidth, fast switching speed, and high power handling capabilities, have made them a popular alternative to PIN diodes, FETs, and complimentary metal-oxide-semiconductor (CMOS) transistors [49].

3. **Other type of analog phase shifters:** Analog phase shifters can also use novel materials like graphene [50] or $Ba_{0.7}$ $Sr_{0.3}$ $TiO_3$ [44]. In [51], 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 14). 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 [51].




(**a**) Geometry of the graphene-based phase shifter




(**b**) prototype of the graphene-based phase shifter and the measurement setup

**Figure 14.** A typical graphene-based phase shifter

In conclusion, the strategy for implementing a phase shifter is determined by various factors, such as frequency range, intended phase resolution, insertion loss level, power consumption, and geometric dimensions. Each strategy has specific benefits and trade-offs regarding performance, size, power consumption, and manufacturing complexity. The following section will provide further information and a comparison of several phase shifters. The research for this thesis primarily focuses on surfaces and liquid metal reconfigurable phase shifters.

## 4. Comparative Studies

In literature, phase shifters are categorized as active phase shifters and passive phase shifters. The advantages and limitations of both are compared in Table 1.

**Table 1.** Comparison between active and passive phase shifters

| Types | Benefits | Limits | References |
|---|---|---|---|
| Active phase shifters | -Lower insertion losses<br>- Architecture simple<br>-Compact geometry<br>-Low cost for silicon surface area. | -Their DC consumption is higher<br>- The linearity is degraded<br>- The transmission power is limited | [5,52] |
| Passive phase shifters | - Reduces DC consumption<br>- Improves linearity. | -The circuits are less compact.<br>Insertion losses are higher | |

The use of passive phase shifters is often restricted to Ku-band and lower due to a number of drawbacks, such as high insertion loss, large size, and narrow bandwidth [53]. Active phase shifters, on the other hand, solve these problems by offering a smaller chip area and a larger gain.

Table 2, compare various topologies currently used to implement phase shifters.

**Table 2.** Comparison between different phase shifter topologies

| *Reference* | *Shift Method* | *Control Type* | *Frequency(GHz)* | *IL* [1]*(dB)* | *RL*[2]*(dB)* | $\Delta\varphi$(°) |
|---|---|---|---|---|---|---|
| [54] | **Switched line** | **Digital** | **13-18** | **2.7** | **22** | **349.3** |
| [55] | **Reflection type** | **Analogue** | **2** | **1** | **13.4** | **385** |
| [56] | **Network type** | **Digital** | **0.5-1** | **2.5** | **13** | **360** |
| [2] | **Loaded transmission line** | **Analogue** | **1** | **2** | **15** | **183** |
| [57] | **GFET CS Amplifier** | **Digital** | **3** | **-2.5** | **0.9** | **197.9** |
| [57] | **GFET CS Amplifier** | **Analogue** | **3** | **0** | **0.4** | **84.5** |
| [32] | **RTPS** | **Digital** | **1.37-1.43** | **2.3** | **>15** | **180** |
| [58] | **Schiffman** | **Digital** | **1.5-6** | **1.2** | **> 10** | **323** |
| [59] | **Inverted-E** | **Digital** | **0.4-4** | **0.46-1.8** | **> 12->15** | **100** |
| [60] | **SUTBRTPSs**[3]**/single-unit** | **-** | **0.9-1.1** | **2.1** | **> 19** | **180** |

Table 3 presents the authors' summary of the various electronic phase shifters' performances [51]. Passive phase shifters, primarily STPS, RTPS, and LLPS, are more linear, have a higher power handling capacity, and use less power than active ones. On the other hand, compared to passive phase shifters, VSPS provide a comparatively larger bandwidth, greater gain, and a smaller chip area. Except for STPS, which is a digital phase shifter, most passive and active electronic phase shifters can be adjusted to provide continuous or discrete resolution. Much recent research has focused on the MEMS solution in an effort to achieve respectable performance regarding power capability, bandwidth, insertion loss, and chip area.

[1] Insertion Loss
[2] Return Loss
[3] Single-Unit Two-Bit Reflection-Type Phase Shifters

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**Table 3.** Comparison of electronic phase shifters

| Performance | STPS [4] | RTPS [5] | LLPS [6] | VSPS [7] |
|---|---|---|---|---|
| Bandwidth | Narrow | Narrow | Narrow | Wide |
| Passive/Active | Passive | Passive | Passive | Active |
| Phase control | Digital | Analog/Digital | Analog/Digital | Analog/Digital |
| 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 shows the benefits and limitations of each type of phase shifter.

**Table 4.** Comparative analysis of phase shifter types

| References | Phase Shifters Type | Benefits | Limits |
|---|---|---|---|
| [54,55,60] | **Ferrites** | -High power-handling capacity<br>-Decent reliability<br>-Radiation tolerance<br>-Suitability for high-power applications | -They are bulky<br>-less integratable<br>-Slow in response (requiring long tuning times)<br>-Expensive (not suitable for mass production)<br>-Significant power consumption |
| [57,58] | **p-i-n diodes, Varactors** | -Offers continuous tunability of the output phase<br>-maintains satisfactory isolation and reflection coefficients<br>-Simple, easy to manufacture<br>-Low cost | -Limited phase-shift resolution<br>- Unacceptably high losses in the millimetre-wave band |
| [59,60] | **MEMS** | -Significantly lower insertion loss<br>-Higher linearity over wide bandwidth<br>-Lower power consumption compared to semiconductor technologies | -Still limited by the maximum operational frequency<br>-Reliability issues |
| [58,59] | **Tunable Dielectrics Methods** | -Easy implementation and control.<br>-Low insertion<br>-High phase resolution<br>-High tunability<br>-Small phase deviation with frequency and linear phase tuning. | -complex configurations<br>-Expensive<br>-High power consumption |
| [61,62] | **Liquid crystal (LC) materials** | -low insertion loss (IL) at higher frequencies.<br>-They offer a wide phase tuning range<br>-High phase resolution | -The phase shifting range of some LC-based designs is limited<br>-Slower switching speed compared to semiconductor-based solutions . |

Much of this study focuses on the advantages of liquid metal characteristics. While liquid metals, such as mercury, have existed and been used since 1500 BC [51], gallium was not discovered until the $19^{th}$ century, and it and its alloys were not discovered as mercury substitutes until the $20^{th}$ century. A summary of the properties of liquid metals based on mercury and gallium is provided.

- **Mercury:** Mercury has been discovered in Egyptian tombs dating back to 1500 BC [62], Mexican pyramids from 1800 years ago, and ancient Chinese and Tibetan histories [51]. While it is

[4] Switched-Type Phase Shifters
[5] Reflective-Type Phase Shifters
[6] Loaded-Transmission Line Phase Shifters
[7] Vector-Sum Phase Shifters

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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 [63]. When combined with other metals, some gallium alloys can have melting points as low as -19 °C (-2 °F) [63], [63]. 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 [64].

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

**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 [65] | Silver [66] | Silver | Silver [67] | Silver |
| **Odor** | Odorless [68] | Odorless | Odorless | Odorless [66] | Odorless |
| **Toxicity** | Hight | Low | Low | Low | Low |
| **Boiling point** | 356.73 °C [40,65] | 2204 °C [67] | Estimated similar to Galinstan® | >1300 °C [67] | Similar to Galinstan® |
| **Melting point** | -38.83 °C [65,67] | 29.76 °C [66,69,70] | ~15.5 °C [69] | -19 °C [67,71] | 11 °C [72], [64] |
| **Density** | 13.534 g/cm3 [65] | 5.904 g/cm3 [66] | 6.2275 g/cm3 [73] | 6.44 g/cm3 [67] | 6.44 g/cm3 [64], [66] |
| **Solubility** | Insoluble [68] | Insoluble | Insoluble | Insoluble [66] | Insoluble |
| **Viscosity** | 1.526 x 10-3 Pa·s @ 25 °C [64] | 1.921 x 10-3 Pa·s @ 50 °C [64] | 1.99 x 10-3 Pa·s [73] | 2.4 x 10-3 Pa·s [63] | ~2.25 x 10-3 Pa·S @ 25 °C [74] |
| **Thermal conductivity** | 8.541 W/(m·K) [64] 8.3 W/(m·K) [65] | 29 W/(m·K) [66] | 26.43 W/(m·K) [74] | 16.5 W/(m·K) [63] | ~25.41 W/(m·K) [66] |
| **Electrical conductivity** | 1.04 x 106 S/m [65] | 7.1 x 106 S/m [66] | 3.46 x 106 S/m [71] 3.4 x 106 S/m [63] | 2.299 x 106 S/m [63] 3.83 ± 0.16 x 106 S/m @ 3-20 GHz | 3.46 x 106 S/m [68] |
| **Surface tension** | >0.4 N/m [71] | >0.5 N/m [75] | >0.5 N/m [75] ~0.624 N/m [70] ~0.435 N/m w/ HCl [71] | >0.5 N/m [75] 534 ± 10.7 mN/m [75] | 0.718 N/m @ 20 °C [66] |

Table 6 presents a detailed analysis of the performance demonstrated by the liquid metal (LM) phase shifter compared to many state-of-the-art LM phase shifters and alternative technologies

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operating at a frequency of 10 GHz. In [62] The suggested LM phase shifters provide low IL and RMS amplitude changes (<1.5 dB in all states). The proposed phase shifters have a better (i.e. lower) IL performance than any other state-of-the-art phase shifters that enable a phase shift of up to 360°. The suggested phase shifters provide exceptional FoM performance of 131.3 and 122.4 °/dB at 10 GHz. This FoM is much greater (i.e., better) than all cutting-edge phase shifters, regardless of the technology utilized. Furthermore, the proposed phase shifters are built on SIW technology and fed by SMA connectors. The proposed phase shifters can handle approximately high amounts of RF power. The proposed work of LM phase shifters[76] achieves low IL and RMS amplitude changes (<1.5 dB across all states). The proposed phase shifters have superior (i.e. lower) IL performance than all state-of-the-art phase shifters with a phase shift of up to 360°. This allows the suggested phase shifters to achieve remarkable FoM performance of 131.3 °/dB and 122.4 °/dB at 10 GHz. This FoM is much higher (i.e. superior) than all cutting-edge phase shifters, regardless of the technology utilized. Furthermore, the proposed phase shifters are built on SIW technology and fed via SMA connectors. The proposed phase shifters can handle high amounts of RF power.

**Table 6.** Performance comparison between the different Liquid metal phase shifters and other alternative phase shifters

| Reference | Technology | Phase shifting(°) | IL(dB) | FoM(°/dB) | Resolution(°) | RMS [8] phase error(°) | RMS amplitude error(dB) | Size(mm) |
|---|---|---|---|---|---|---|---|---|
| [76] | Liquid Metal | 367.6 | <2.8 | 13.3 | ≈ 45 | 20 | <1.5 | 57.2*14 |
| [77] | Liquid Metal | 180 | 2.3 | 78.3 | 10 | 10 | NA | 87.2*56.2 |
| [78] | Liquid Metal(Non Uniform) | 367.6 | <2.8 | 131.3 | ≈ 45 | 20 | <1.5 | 57.2*14 |
| [78] | Liquid Metal(Uniform) | 379.5 | <3.1 | 122.4 | ≈ 45 | 20 | <1.5 | 57.2*14 |
| [79] | Ferroelectric based | 413 | 10.3 | 40.1 | NA | NA | >3 | 3.8*2.3 |
| [80] | Ferrite-LTCCC | 215 | <7 | 48 | NA | NA | NA | ≈ 45*45 |
| [81] | Liquid Crystal | ≈ 60 | 2.5 | 24 | NA | NA | NA | NA |
| [82] | Liquid Crystal | ≈ 101 | ≈ 5 | 15.2 | NA | NA | NA | NA |
| [83] | Liquid Crystal | 461 | 4.35 | 105.9 | NA | NA | NA | NA |
| [84] | GaN | 180 | 14 | 12.8 | 11.25 | 4.5 | ≈ 0.6 | 4.7*5 |
| [85] | 0.25 µm SiGe BiCMOS | 360 | <12 | <30 | 11.25 | 6.4 | >3.0 | 1.87*0.88 |
| [86] | 0.13 µm CMOS | 360 | | 27.3 | 5.625 | 4.1 | ≈ 0.8 | 2.06 × 0.58 |
| [87] | 0.18 µm SiGe BiCMOS | 360 | 11.9 | 30.25 | 5.625 | 4.6 | ≈ 0.6 | NA |
| [88] | 0.25 µm SiGe BiCMOS | 360 | ≈ 13 | 27.7 | 5.625 | 4 | ≈ 0.6 | 3.42 × 0.95 |
| [88] | PIN Diode-SIW | <180 | ≈ 2 | ≈ 90 | NA | NA | >0.8 | NA |

## 5. Applications

Phase shifters, as one of the most significant devices, play an important role in the development of reconfigurable PICs. Many high-performance reconfigurable devices based on phase shifters have been proposed, such as modulators [39,89], optical filters [90,91], and tunable delay lines [92]. In addition, efficient phase shifters with a low power consumption and high modulation speed pave the way for large-scale neuromorphic computing systems, photonic accelerators, optical phased arrays, on-chip spectrometers, etc. In this section, we will introduce the phase shifter-based reconfigurable According to the literature we find :

- **Advanced Optical Computing Systems**: Traditional computers built on the von Neumann architecture, which physically divides the processing module from the storage module, are encountering speed and integration density limits in the post-Moore era. To overcome Moore's Law's constraints, many scientists started investigating the upcoming generation of computer architectures and presented some intriguing computing platforms. we find two types:
  - **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. Thanks to its accurate and adjustable steering angle of emitted light, OPAs have emerged as a strong contender for spatially resolved optical sensors,

[8] Root Mean Square

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**: Perez et al. proposed a hexagonal mesh structure inspired by FPGAs in the field of electronics [93]. This structure has a phase shifter on each side of the hexagon, enabling a particularly large number of functions, including ring-loaded MZIs, optical ring resonators, coupler resonator waveguides, side-coupler integrated spaced sequences of optical resonators, and single-input/single-output FIR filters. 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 [94,95]. 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.

## 6. Challenges and Future Trends of Phase Shifters for Phased Array Systems

### *6.1. Liquid Metal-Based Phase Shifters*

Liquid metals have been utilized to create reconfigurable components, including filters, frequency-selective surfaces, and antennas because they enable more versatile tunable systems. In the comparative study section, we previously discussed various types of phase shifters. In this section, our specific focus is on phase shifters and reconfigurable liquid metal surfaces. Our study revolves around identifying and addressing the issues associated with this type, as well as improving upon it. Furthermore, we will present table 7 that outlines different liquid metal-based phase shifters and their limitations based on recent research findings.

**Table 7.** Comparative Analysis of Liquid Metal phase shifters

| Ref. | Liquid Metal | Benefits | Limits |
|---|---|---|---|
| 1 | Galinstan | -Enable reversibility and reconfigurability of the phase shifter.<br>-Provide a wide operating frequency range suitable for various applications.<br>-Provide flexibility<br>-Efficient performance | -Limitation in the frequency range<br>-Nonlinearity |
| 2 | Galinstan R and EGaIn | -Offers stretchability<br>-Ensures safety in handling and operation<br>-High performance | -Hight weight and sagging<br>-Air gaps<br>-Fabrication Complexity |
| 3 | Gallium | -Reconfigurability: which combines the advantages of planar antennas with millimeter wave and Internet of Things technologies.<br>-Wide Phase Shift Range.<br>-Low Insertion Loss. | -Reconfiguration speed.<br>-Fabrication Complexity.<br>-Reliability Issues.<br>-Performance Restrictions. |
| 4 | Gallium | -Reconfigurability,Liquid metal can be easily reconfigured.<br>-Wide Phase Shifting Range.<br>Low Insertion Loss.<br>-Compact Design. | - Have an impact on performance.<br>-Corrosion and Oxidation.<br>-Cost: expensive than using conventional solid-state materials |
| 5 | Gallium | -Wide range of phase shift (0° to 360°).<br>-Operation at 10 GHz with low insertion losses, suitable for high-power RF applications.<br>-Exceptionally low insertion loss.<br>-Compact electrical footprint | -Differences between measured and simulated phase responses<br>-The use of liquid metal into the SIW framework has presented challenges with dependability and longevity.<br>-Possible need for additional optimization to resolve differences in performance |
| 6 | Galinstan EGaIN | -Large Phase Tuning Ratio<br>-Low Insertion Loss<br>-Compact Design<br>-High Power Handling Capability | -Impact on RF Performance<br>-Size Considerations<br>-Fabrication Difficulties<br>-Integrity Maintenance |

 doi:10.20944/preprints202411.1386.v1



The previous 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.

### *6.2. Future Trends of Phase Shifters for Phased Array Systems*

Among beam-steering techniques, phased array antenna techniques remain the most common due to their unique benefits, which include high SNR/SIR, wide coverage, and high scanning speed. This is especially true in light of the expanding 5G communication systems and beyond. Present 5G wireless systems are anticipated to continue utilizing mm-wave bands in order to meet the bandwidth needs of billions of connected devices, and they can provide up to 10 GB/S of data flow with 1 ms latency [96]. 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 [6,64].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 [64]. The design of low-cost and low-loss beamforming and power-feeding networks are 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 lately [96]. On the other hand, the mm-wave BM structures need extremely tiny lines, which are challenging to make. Therefore, in order to get over this restriction, future research on BM feeding networks will involve creating strategies such 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. In order to create novel beamforming networks with fewer phase shifters at mm-wave frequencies, more research is therefore required.

## 7. Conclusions

This detailed review offers a thorough analysis of phase shifters, with a specific focus on liquid metal phase shifters. It includes performance comparisons and discusses future directions in this field. The review identifies critical challenges faced by liquid metal phase shifters, considers size considerations and architecture, and covers a wide range of frequency bands to enhance overall performance. The review suggests that future research could focus on improving and advancing liquid metal phase shifters, potentially through miniaturization to increase their potential applications.

Additionally, a smaller phase shifter would be easier to handle and adjust when tuning the phase shift. The review emphasizes the importance of assessing multiple performance metrics. it serves as a valuable resource for researchers and engineers involved in the design of liquid metal phase shifters for various applications. It also highlights key challenges and future directions in this field.Hence, to lower the overall cost of phased array systems for wireless 5G communication systems, future work will involve building appropriate feeding networks that require less complicated fabrication procedures and implementing phase shifters with minimal phase errors and loss utilizing cost-effective technologies.

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 doi:10.20944/preprints202411.1386.v1




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