Tunable phase shifter in substrate integrated waveguide

Ruo Feng Xu[^1], Yan Li Li[^1], Benito Saenz Izquierdo[^2], and Paul R. Young[^2]

Abstract In this paper, a variable substrate integrated waveguide (SIW) phase shifter is presented. The phase shifter is formed by capacitively coupling varactors to a longitudinal slot on a SIW. Compared to other SIW phase shifters, our design is tunable, and only occupies 7.5 mm longitudinal length. Experiment results indicate the device is shown to have up to 60 degrees phase shift in the 5.3–6 GHz range with insertion loss better than 3 dB and return loss generally better than 20 dB.

Keywords: substrate integrated waveguide (SIW), phase shifter, varactor

Classification: Microwave and millimeter-wave devices, circuits, and modules

1. Introduction

Phase shifters are one of the most important devices in signal transmission and find application in communication [1, 2], measurement and instrumentation systems [3, 4]. They are also particularly important in radar systems [5, 6, 7, 8] where they provide the required phase change between the antenna elements of a phased array for beam steering in antenna arrays.

In recent years there has been a great deal of interest in substrate integrated waveguides (SIW) formed using standard microwave circuit fabrication techniques [9, 10, 11, 12]. Substrate integrated waveguides have all the advantages such as low loss and high quality factor that conventional rectangular waveguide has over planar transmission lines with the added advantage of being inherently integratable with planar circuits and excellent immunity to electromagnetic interference [13, 14, 15]. As a key control element, the varactor diode is easy to tune the distributing capacitance, which can be used to form the integrated circuits. Due to the insignificant cross-talk between adjacent waveguides, SIWs are particularly appropriate for forming antenna arrays [16, 17, 18, 19, 20]. The linear capacitance shifting along the top slot on the waveguide determines the phase velocity and the gain [21, 22, 23, 24].

In this letter we present a substrate integrated waveguide variable phase shifter. The device is formed by capacitively loading a slotted waveguide with varactor diodes. Compared to previous SIW phase shifters [25, 26, 27] our structure is tunable and very simple to fabricate.

The design may find application in beam steerable antenna arrays formed in SIW.

2. Design of tunable phase shifter in substrate integrated waveguide

The host line of our structure is a substrate integrated waveguide with a longitudinal slot running along the top metallic plane. The slot loads the waveguide with a small capacitance which slightly alters the cut-off frequency of the un-slotted guide. However, if we load the slot with varactors, a much larger capacitance loads the waveguide which can greatly alter the propagation characteristics. Furthermore, by using varactors the capacitance can be varied by changing the diode bias.

The phase constant \( \beta \) of a waveguide is related to the cut-off frequency \( f_c \) via the familiar equation:

\[
\beta = k \sqrt{1 - \left( \frac{f_c}{f} \right)^2}
\]

where \( k \) is the wavenumber in the substrate material and \( f \) is the working frequency. The loaded impedance is a decisive factor altering the cut-off frequency for a slotted SIW. In our design, the loaded impedance \( Z \) along the slot is formed by the discrete capacitance \( C \), which is provided by varactors with period much less than a wavelength.

In Fig. 1(a), the loaded impedance \( Z \) occupies the slot \( d \) between the long side \( L_1 \) and short side \( L_2 \). The propagation occurs under the resonance condition: \( Z_{a1} = -Z_{a2} \) \[28\], where \( Z_{a1} \) is the left impedance of the slot and \( Z_{a2} \) is the impedance at the same point looking towards to the right. At the resonance point, the condition of this equivalent transverse circuit can be demonstrated as:

\[
jZ_0 \tan k_c L_1 = -(Z + jZ_0 \tan k_c L_2)
\]

where \( k_c \) is the wavevector in the waveguide. In TE mode, the equivalent voltage \( V \) and current \( I \) are set equal to the vertical electric \( (E_z) \) and longitudinal magnetic \( (H_z) \) fields respectively \[29\]. If the electric field is independent vertically, then the impedance voltage will be \( E_zb \), where \( b \) is the height of the waveguide. Hence above the cut-off situation, the characteristic impedance is given by \( Z_0 = E_z/H_z = bF/I = b\omega\mu/k_c \), where \( \omega \) is the working frequency and \( \mu \) is the relative magnetic permeability of the dielectric material.

The discrete capacitance \( C \) is represented as the impedance per unit length. At the fundamental mode, the cut-off frequency \( f_c \) of host SIW can be approximately calculated by equation (2), which is \( f_c = 1/2\pi\sqrt{\mu Cb(L_1 + L_2)} \) \[30\].

[^1]: School of Information and Control Engineering, China University of Mining and Technology, Xuzhou 221116, China
[^2]: School of Engineering and Digital Arts, University of Kent, Canterbury, Kent, CT2 7NT, United Kingdom

DOI: 10.1587/elex.16.20190489

Received July 29, 2019
Accepted August 28, 2019
Publicized September 9, 2019
Copyedited October 10, 2019

Copyright © 2019 The Institute of Electronics, Information and Communication Engineers
Corresponding to equation (1), the increase of capacitance $C$ will directly lead to the same trend of phase constant $\beta$. Thus, by changing the varactor bias we can variably change the phase shift $\beta L$ over a given length $L$ of the waveguide.

To demonstrate the device, the host SIW is fed by 50Ω microstrip transmission lines which taper to provide a match to the waveguide. The SIW is fabricated using the Rogers 5870 material with dielectric constant $\varepsilon_r = 2.33$ and 1.575 mm thickness. The total length of the guide is 120 mm and the width is 21 mm. This results in a cut-off frequency of approximately 4.7 GHz. The slot on the top is 0.5 mm in width $d$ and positioned 5.5 mm from the right sidewall. The sidewalls are formed by a series of metallised vias. The varicators are the BB857 SAT-TV varicap diode which has a range of capacitance from 0.45 pF to 7.2 pF. Only two diodes are used the separation between them being 2.5 mm.

Waveguide is a single conductor structure and therefore to bias the diodes the varactors cannot be directly connected to the slot. Therefore, to integrate the varactors with the SIW we place a very thin insulator above the waveguide with two copper plates on its top. The diodes are connected between the two plates which capacitively couples them to the waveguide. A similar biasing technique has recently been used in tunable frequency selective surfaces [31]. The distance between the two copper tapes is 2.5 mm; the larger copper plate has approximate dimensions of 2.5 mm $\times$ 9 mm and the smaller one is 2.5 mm $\times$ 3 mm. The total length of the phase shifter is therefore 7.5 mm. The dielectric of insulator has a dielectric constant of approximately 2 and has thickness of 60 µm. A dual 35 V power supply provides the tunable voltage to the plates. RF chokes are used to avoid coupling to the bias wires. A photograph of the structure and its cross-sectional geometry is shown in Fig. 1(b)(c).

### 3. Experiment results

The phase shifter was measured using an Anritsu 37397C network analyzer with coaxial calibration. SMA connectors were soldered to the microstrip feed lines and used to connect to the analyzer. The effect of the SMA connectors was not de-embedded from the measurement.

Fig. 2 shows the measured phase changes (difference in phase shift between zero and biased condition) for various bias voltages. As we can see a phase shift of greater than 150 degrees can be achieved at 5 GHz for high bias values. However, we find that at this point the insertion and return loss are poor because the waveguide approaches cut-off at this frequency and therefore the operation of the phase shifter should be limited to above 5.3 GHz.

Fig. 3 shows the measured insertion loss of the structure at 5.3, 5.5, 5.7 and 6 GHz as a function of bias. As can be seen the insertion loss is increased at low frequencies where the waveguide approaches cut-off. This is particularly so for large bias voltages. However, if we limit the bias to 20 or 25 V then the insertion loss is generally lower than 3 dB over the 5.3–6 GHz range. With reference to

---

**Fig. 1.** (a) Equivalent transverse circuit of slotted SIW (b) Cross-sectional geometry of the phase shifter with bias circuits (c) Top view and photograph of the phase shifter.

**Fig. 2.** Measured phase change as a function of frequency for different bias voltages.

Fig. 2 this implies that a maximum phase shift of 60 degrees is obtainable at 5.3 GHz with 20 V bias and acceptable insertion loss. The return loss is below 10 dB over the entire range and generally below 20 dB.
A maximum phase shift of 60 degrees with acceptable return and insertion loss has been demonstrated. Additional phase shift could be achieved by increasing the number of loading diodes. The design has been demonstrated at 5 GHz but could easily be scaled for millimeter-wave applications using suitable diodes. The phase shifter may find application in steerable antenna arrays formed in SIW.

4. Conclusion

A SIW phase shifter has been presented. Compared to other SIW phase shifters, our design is tunable, and the control section only occupies 7.5 mm longitudinal length. A maximum phase shift of 60 degrees with acceptable return and insertion loss has been demonstrated. Additional phase shift could be achieved by increasing the number of loading diodes. The design has been demonstrated at 5 GHz but could easily be scaled for millimeter-wave applications using suitable diodes. The phase shifter may find application in steerable antenna arrays formed in SIW.

Acknowledgments

The work was supported by the NSFC program (grant numbers: 51507176).

References


Fig. 3. Measured insertion loss as a function of bias voltage for different operating frequencies.

Fig. 4. Measured phase shift as a function of voltage for different operating frequencies.


