K-Band Substrate Integrated Waveguide Variable Phase Shifter

Deisy Formiga Mamedes[1], Mahbubeh Esmaeili[2], Jens Bornemann[2]
[1] Dept. of Electrical Engineering, Federal Institute of Education, Science and Technology of Paraíba, João Pessoa, PB, Brazil
[2] Dept of Electrical and Computer Engineering, University of Victoria, Victoria, BC, V8W 2Y2, Canada

***Abstract*— A substrate integrated waveguide (SIW) variable phase shifter for K-band applications is presented that can be straightforwardly integrated with other SIW antenna feed circuitry. Biasing of two varactor diodes provides continuous control of the phase shift. The results demonstrate that the proposed structure has a wide phase tuning range, flat insertion loss and low reflection coefficient over a wide frequency band. Experimental results confirm that the phase can be shifted by up to 200 degrees at one frequency and by about 140 degrees for the rest of the band. Insertion losses are measured at 4 dB, and the return loss is better than 10 dB.**

***Index Terms*—phase shifter, substrate integrated waveguide, feed network, varactor diode.**

I. Introduction

As bandwidth requirements increase due to demands for higher data rate, the operating frequency of future wireless networks will surpass 20 GHz and even increase into the millimeter-wave range bands [1]. For such applications, it is important to develop planar technologies including antennas that can straightforwardly be incorporated in highly integrated millimeter-wave systems.

In such frequency ranges, substrate integrated waveguide (SIW) technology has proven to be a promising alternative to conventional waveguide and microstrip circuitry [2]. Therefore, in addition to individual SIW antennas, arrays and feed networks for fixed beam applications have been increasingly designed within the SIW concept [3] - [6].

In order to adapt an array for a preferred direction, however, devices involving phase variations are required to rapidly steer and direct the beam [7], [8]. Therefore, SIW phase shifters have been designed which are compatible with printed-circuit manufacturing techniques and on-board device placement [9], [10]. However, those components are for Ku-band operation and percentage bandwidths of 4 percent and 15 percent, respectively.

This paper focuses on an SIW reflection-type variable phase shifter design for K-band applications. By employing only two varactor diodes (as opposed to four in [10]), the phase can be varied over a 15.7 percent bandwidth centered at 20.4 GHz while insertion losses are comparable with those of [10] and return losses remain below 10 dB.

The authors would like to acknowledge financial support for this work by MITACS and the TELUS Grant in Wireless Communications, Canada as well as the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, CAPES, Brazil.

II. Design

The design of the reflection-type phase shifter involves a three-step process. First, an SIW 3-dB coupler is designed. Secondly, SIW-to-microstrip transitions are added as shown in Fig. 1. At the reflecting ports 3 and 4, they are later required to accommodate the varactor diodes. At the input (1) and output (2) ports, they are bent to provide access for measurement equipment. Note that the transitions at ports 1 and 2 can be eliminated in an actual SIW feed network design as those ports will be connected to other SIW circuitry. Thirdly, the varactor diodes will be selected to provide the desired phase shift based on the biasing voltage.

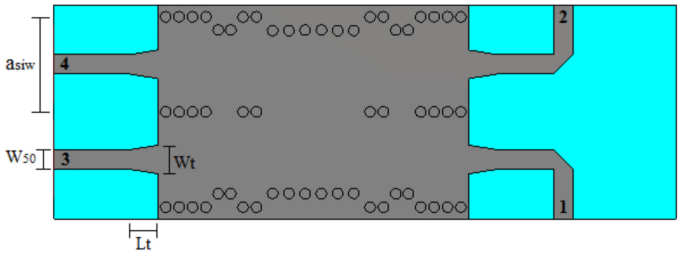

Fig. 1. SIW coupler with microstrip ports.

A. Coupler Design

The SIW coupler used for this application is a variation of the one presented in [11]. In the design process, the coupler can be first designed in all-dielectric waveguide technology where the cutoff frequency f_c specifies the equivalent waveguide width W_{equi}

$$W_{equi} = \frac{c}{2 f_c \sqrt{\varepsilon_r}} \tag{1}$$

with ε_r being the permittivity of the substrate and c the speed of light in free space. The chosen substrate is RT/Duroid 6002 with relative permittivity of 2.94 and height of h = 508 µm. The translation to the respective SIW widths (a_{SIW} in Fig. 1) is given by [12]

$$a_{SIW} = W_{equi} + p\left(0.766 e^{0.4482 d/p} - 1.176 e^{-1.214 d/p}\right) \tag{2}$$

for given via diameter d and via pitch p (c.f. Table I).

B. Microstrip Transitions

The microstrip-to-SIW transitions are designed according to [13]. For a given width W_{50} of the 50-Ω microstrip line (Fig. 1, Table I), the following equation is solved for W_t

$$\frac{1}{h\left[\frac{W_t}{h}+1.393+0.667\ln\left(\frac{W_t}{h}+1.444\right)\right]}=\frac{4.38}{W_{equi}}\exp\left(-0.627\frac{\varepsilon_r}{\varepsilon_e}\right) \quad (3)$$

with $L_t=\frac{\lambda_g}{4}$, $\lambda_g=\frac{c}{f\sqrt{\varepsilon_r}}$ and

$$\varepsilon_e=\frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{\sqrt{1+12\frac{h}{W_t}}} \quad (4)$$

The so-obtained dimensions of the microstrip transitions are summarized in Table I.

TABLE I. DIMENSIONS OF MICROSTRIP TRANSITIONS

Parameter	Value (mm)
a_{siw}	6.30
d	0.70
p	1.00
W_{50}	1.28
Wt	1.89
Lt	1.90
$Wequi$	5.75

Fig. 2 shows the performance of the K-band SIW directional coupler with microstrip ports as simulated in CST Microwave Studio. Return loss and isolation are better than 10 dB between 18 and 27.5 GHz. Since coupled and through ports signals join at -5 dB, the insertion loss of the entire coupler amounts to about 2 dB.

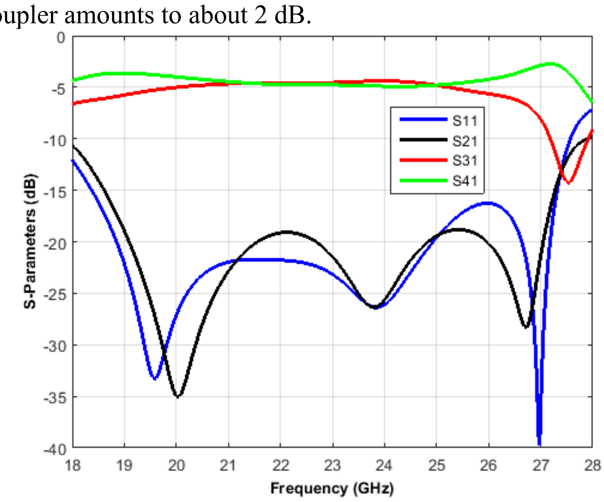

Fig. 2. Simulated performance of SIW coupler with microstrip ports.

C. Varactor Diodes

The first step to determine the required phase shift is to insert capacitors at ports 3 and 4 of the coupler as shown in Fig. 3. As the capacitances are varied between 0.1 pF to 100 pF for a frequency of 23 GHz (Fig. 4a), it is observed that low capacitance values provide higher phase variation. Therefore, the range of low capacitance is depicted in Fig. 4b which shows a phase variation of approximately 80 degrees.

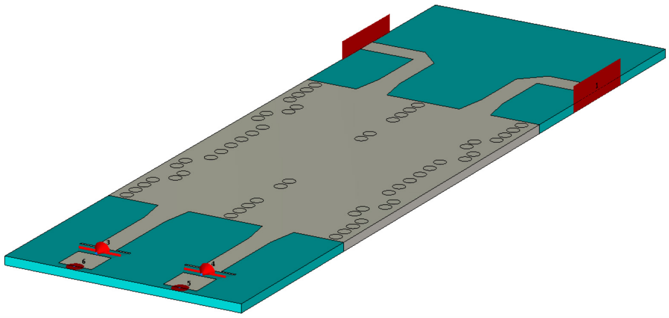

Fig. 3. Coupler with capacitors.

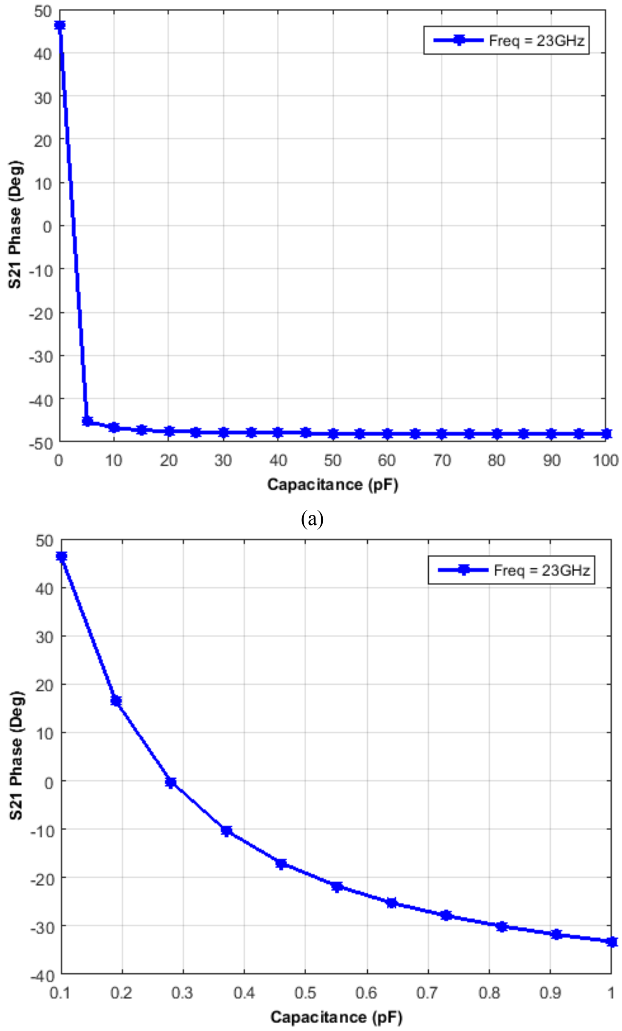

Fig. 4. Transmission phase ($<S_{21}$) versus capacitance; (a) up to 100 pF, (b) up to 1 pF.

In order to provide appropriate capacitance, parasitic compensation stubs of 150 µm width and 4.5 mm length are placed in parallel to the selected varactor diodes, SMV2201-040LF. Both varactor diodes are connected in series to inductors and a voltage source. The inductors provide quasi-open circuits for the RF so that the varying capacitances of the varactor diodes resemble open line sections of variable lengths.

The circuit is simulated in CST, and the capacitance values range from 0.23 pF to 2.10 pF when applying a biasing voltage between 0 V and 20 V [14]. Fig. 5 presents the simulated phase of S_{21} which is about 180 degrees at 19 GHz and 105 degrees at 22 GHz. The exact phase values at three different frequencies are summarized in Table II.

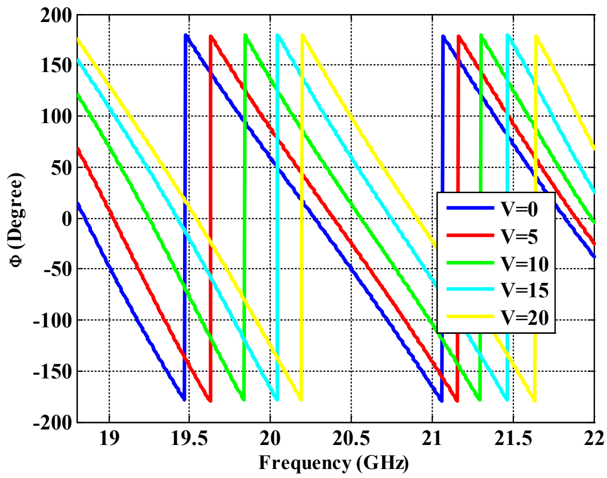

Fig. 5. Simulated S_{21} phase for different values of biasing voltage.

TABLE II. PHASE FOR DIFFERENT VALUES OF BIASING VOLTAGE AND FREQUENCY

Frequency -> Voltage	19 GHz	20.5 GHz	22 GHz
0V	–48	–49	–34
5V	6	–28	–21
10V	64	14	–4
15V	108	60	29
20V	130	100	70

III. RESULTS

Fig. 6 shows a prototype of the K-band variable phase shifter within the test fixture for measurements.

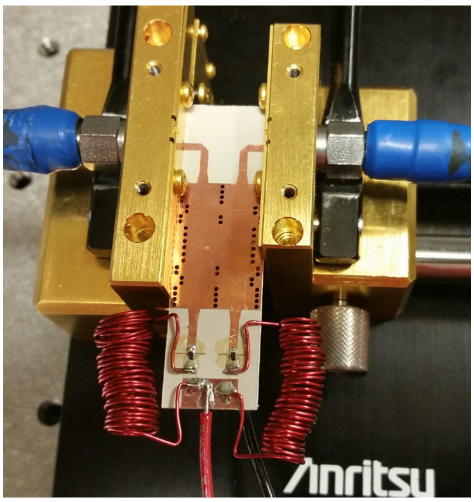

Fig. 6 K-band SIW variable phase shifter prototype.

From top to bottom, the following components can be observed: SIW coupler with microstrip transitions, capacitive stubs at the straight microstrip lines, varactor diodes, inductors, and the wire to provide the biasing voltage.

Fig. 7 shows the S-parameters result of the SIW phase shifter. Good agreement between measured and simulated results is observed. The overall insertion loss is around 4 dB, and the return loss is better than 12dB from 18.8 GHz to 22 GHz. These performance values are comparable with those in [10].

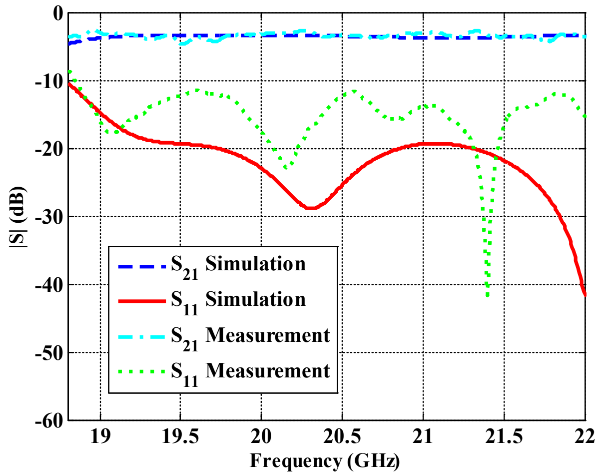

Fig. 7 Simulated and measured S parameters of the K-band SIW variable phase shifter.

In order to compare measured and simulated phase shifts, we display in Fig. 8 the differential phase shift between zero and full biasing voltage as

$$\Delta\Phi = \left| \sphericalangle(S_{21})_{V=0} - \sphericalangle(S_{21})_{V=V_0} \right| \qquad (5)$$

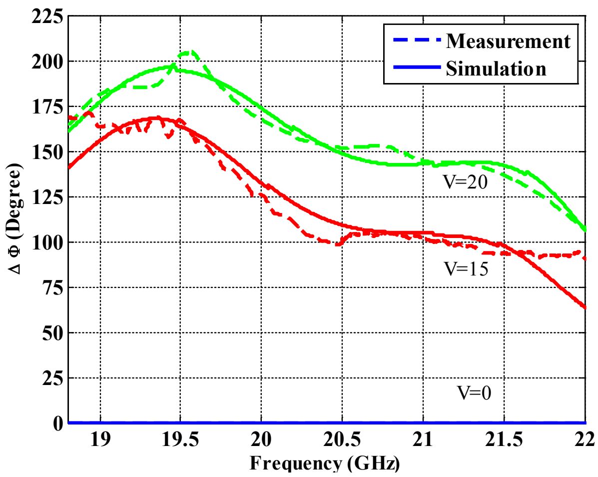

Fig. 8 Simulated and measured phase difference of the K-band SIW variable phase shifter.

First of all, we observe good agreement between simulated and experimental results. Secondly, the differential phase shift can be varied between 0 degrees and a maximum of about 200 degrees at 19.5 GHz. Above this frequency, the differential phase shift tapers down to about 140 degrees at 21 GHz to 21.5 GHz, and finally arrives at 110 degrees at 22 GHz. Note that this downward drift is also observed in [10] where the phase difference decreases from about 170 degrees at 12 GHz to 110 degrees at 13.8 GHz.

IV. Conclusions

A K-band SIW variable phase shifter is presented for applications in the 18.8 – 22 GHz range. Simulated and experimental results demonstrate that the phase can be shifted by varying the capacitances of two varactor diodes to a maximum value of 200 degrees. Compared to a previous design in half-mode SIW [10], insertion losses, return losses and the phase shifting range are similar. However, the circuit presented here operates at a higher frequency, provides a similar percentage bandwidth (15.7 percent versus 15.4 percent) and uses only two varactor diodes instead of four. It is expected that the current design is suitable for high-density SIW millimeter wave applications.

References

[1] T.S. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G.N. Wong, J.K. Schulz, M.Samimi, and F. Gutierrez, “Millimeter wave mobile communications for 5G cellular: It will work!” IEEE Access, vol. 1, pp. 335-349, 2013.

[2] K. Wu, “State-of-the-art and future perspective of substrate integrated circuits (SICs),” in Workshop Notes, *IEEE MTT-S Int. Microw. Symp. Dig.*, Anaheim, USA, May 2010.

[3] S. Lin, S. Yang, and A. E. Fathy, “Development of a novel UWB Vivaldi antenna array using SIW technology,” Prog. Electromagn. Res., vol. 90, pp. 369–384, 2009.

[4] N. Ghassemi, K. Wu, S. Claude, X. Zhang, and J. Bornemann, “Low-cost and high-efficient W-band substrate integrated waveguide antenna array made of printed circuit board process,” IEEE Trans. Antennas Propagat., vol. 60, pp. 1648–1653, Mar. 2012.

[5] K. Wu, Y.J. Cheng, T. Djerafi, and W. Hong, “Substrate-integrated millimeter-wave and terahertz antenna technology,” Proc. IEEE, vol. 100, pp. 2219-2232, July 2012.

[6] D.-F. Guan, C. Ding, Z.-P. Qian, Y.-S. Zhang, W.-Q. Cao, and E. Dutkiewicz, “An SIW-based large-scale corporate-feed array antenna,” IEEE Trans. Antennas Propagat., vol. 63, pp. 2969–2976, July 2015.

[7] W.M. Abdel-Wahab and S. Safavi-Naeini, “Low loss H-shape SIW hybrid coupler for millimeter-wave phased arrays antenna systems,” in IEEE AP-S Int. Symp. Dig., Chicago, USA, 2012, pp.1-2.

[8] H. Zhou, W. Hong, L. Tian, and L. Cheng, “A compact passive retrodirective antenna array with SIW phase shifters integrated,” 2015 in IEEE Int. Wireless Symp. Dig., Shenzhen, China, 2015, pp. 1-4.

[9] E. Sbarra, L. Marcaccioli, R.V. Gatti, and R. Sorrentino, “Ku-band analogue phase shifter in SIW technology,” in Proc. 39th Eur. Microw. Conf., Rome, Italy, 2011, pp. 264-267.

[10] J. Li, J. Chen, P. Chen, and F. Zhu, “Varactor-tuned half mode substrate integrated waveguide reflection-type phase shifter,” in Proc. IEEE MTT-S Int. Microw. Workshop Ser., Nanjing, China, pp. 1-3.

[11] Z. Kordiboroujeni, J. Bornemann, and T. Sieverding, “Mode-matching design of substrate-integrated waveguide couplers,” in Proc. Asia-Pacific Int. Symp. Electromagnetic Compatibility, Singapore, May 2012, pp. 701-704.

[12] Z. Kordiboroujeni and J. Bornemann, “Designing the width of substrate integrated waveguide structures,” IEEE Microw. Wireless Compon. Lett., vol. 23, pp. 518-520, Oct. 2013.

[13] D. Deslandes and K. Wu, “Design equations for tapered microstrip-to-substrate integrated waveguide transitions”, in IEEE MTT-S Int. Microw. Symp. Dig., Anaheim, USA, May 2010, pp. 704-707.

[14] SMV220X Varactor Diode Datasheet, http://www.skyworksinc.com /uploads/documents/201953A.pdf.