A Compact, 37% Fractional Bandwidth Millimeter-wave Phase Shifter Using a Wideband Lange Coupler for 60-GHz and E-band Systems

Navid Hosseinzadeh and James F. Buckwalter

Electrical and Computer Engineering Department, University of California at Santa Barbara,
Santa Barbara, CA, 93106, USA

***Abstract*—A wideband 57.7-84.2 GHz Phase Shifter is presented using a compact Lange coupler to generate in-phase and quadrature signal. The Lange coupler is followed by two balun transformers that provide the IQ vector modulation with differential I and Q signals. The implemented Phase Shifter demonstrates an average 6-dB insertion loss and 5-dB gain variation. The measured average rms phase and gain errors are 7 degrees and 1 dB, respectively. The phase shifter is implemented in GlobalFoundries 45-nm SOI CMOS technology using a trap-rich substrate. The chip area is 385 μm $\times$ 285 μm and the Phase Shifter consumes less than 17 mW. To the best of authors knowledge, this is the first phase shifter that covers both 60 GHz band and E-band frequencies with a fractional bandwidth of 37%.**

***Index Terms*—phase shifter, SOI CMOS, IQ vector modulator, phased array, Lange Coupler, wideband, 60 GHz, E-band**

I. Introduction

The development of phased array systems for 5G applications places critical requirements on the power consumption of array components. Existing WiGiG systems at 57-64 GHz are now being expanded with recent FCC allocation of unlicensed bands between 64-71 GHz. When considering previous E-band backhaul bands at 71-76 and 81-86 GHz, this provides the potential applications of phased arrays that would cover 57-86 GHz across three potential bands. Consequently, a growing need exists for wideband millimeter-wave components such as phase shifters that will enable wideband phased arrays that are compatible with any of these bands or even multiple bands simultaneously.

Phase shifters are critical components for RF beamforming arrays as they dictate the insertion loss, power consumption, and linearity of the RF front-end. A number of papers have been presented over the last decade to optimize different performance characteristics of millimeter wave phase shifters [1]–[9]. These phase shifters are typically categorized between passive phase shifters based on reflection-based phase shift or switch phase delays and active phase shifters based on I/Q vector modulators. Passive phase shifters typically have excellent linearity but are discrete and have high insertion loss. Additionally, passive phase shift networks are typically narrowband. In this demonstration, we focus on demonstrating a high fractional bandwidth while providing continuous phase control through a weighted vector modulator.

II. Phase Shifter Architecture

The proposed phase shifter circuit, shown in Fig. 1, is based on a single-ended input and output ports. This makes the

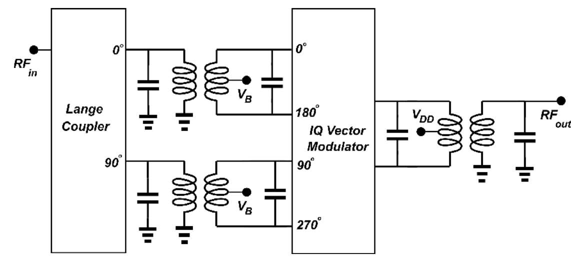

Fig. 1. Block diagram of millimeter-wave Phased Shifter based on an I/Q vector modulator.

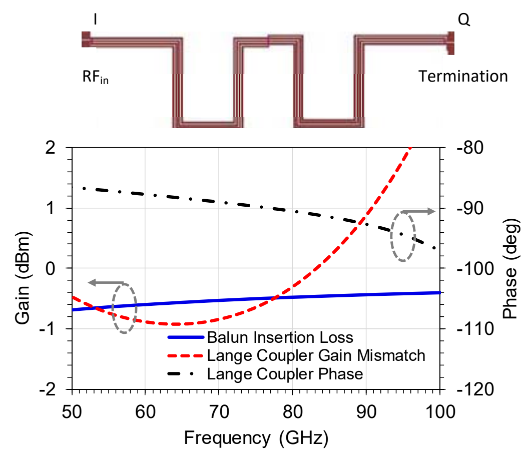

Fig. 2. Layout of the Lange Coupler (top), EM simulations of the balun insertion loss, Lange coupler gain mismatch, and Lange coupler phase shift between outputs across the frequency range (bottom).

phase shifter design appropriate for insertion into a phased array based on single-ended multi-element power combiners and single-ended amplifiers. The input signal is introduced to a Lange coupler which provides in-phase (I) and quadrature (Q) signal components and then a pair of baluns that produce the differential I and Q components, 0°, 90°,180°, and 270°, to produce a vector weighted sum of the I and Q components. The differential output from the I/Q vector modulator is then introduced to a balun to produce a single-ended signal.

While the I/Q vector modulator is inherently a broadband circuit, the bandwidth limitation of the phase shifter tends to be limited by the I/Q signal generation and the baluns.

978-1-5090-6069-6/17/$31.00 ©2017 IEEE

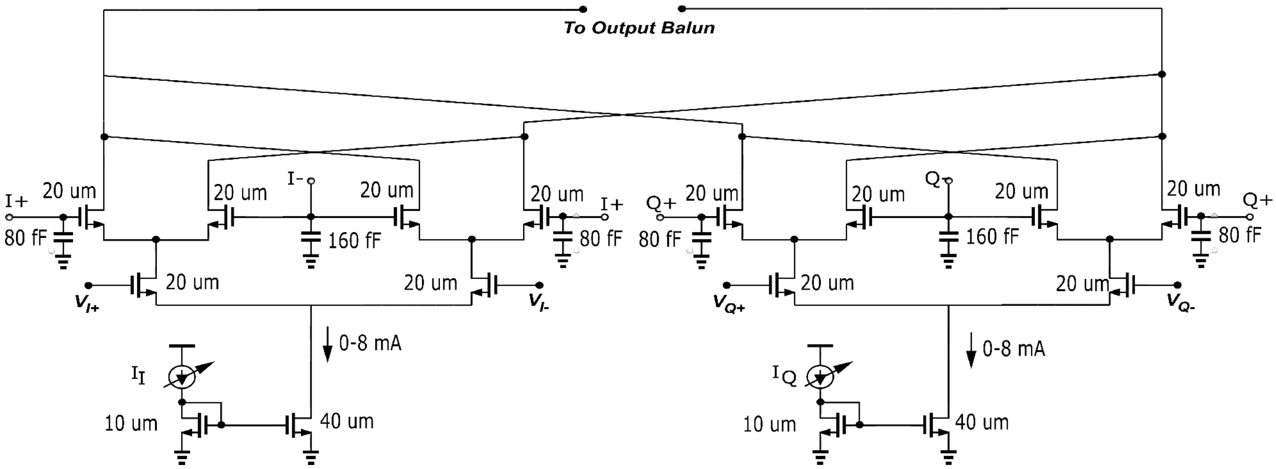

Fig. 3. Schematic of the IQ vector modulator.

A. I/Q Signal Generator

At low frequencies, polyphase filters have been used to generate I and Q signal components. While polyphase filters produce a wideband phase shift, the amplitude mismatch between the I and Q components is poor for wide bandwidth. The bandwidth can be enhanced by using inductors in the polyphase network as demonstrated [5], [10]. The main advantage of the polyphase filter over a microwave I/Q generator is the small footprint at low frequency.

At mm-wave frequencies, 90° hybrids such as the Lange coupler or branchline coupler have increasingly compact footprints due to the reduce length of the transmission line to implement a phase shift. Additionally, the aspect ratio of the hybrid can be adjusted by routing the hybrid in a serpentine pattern. Fig. 2 shows the layout of the Lange coupler. As shown, a very compact Lange coupler is demonstrated to generate I and Q signal components. As it can be seen in Fig. 2, the coupler size is adjusted through two U-shaped bends. The Lange coupler is then followed by two baluns that provide differential I and Q signals. The performances of the Lange coupler and baluns are carefully modeled using EMX tool and optimized for bandwidth. Fig. 2 shows the insertion loss of the balun is predicted to be under 0.8 dB from 50 to 100 GHz. The gain mismatch of the Lange coupler is under 1 dB from 50 to 90 GHz and the phase difference between the Lange coupler outputs is less than +-4 degrees from 50 -90 GHz.

An additional benefit of using a 90° hybrid at the input of the phase shifter circuit is improvement of the input return loss as reflected signals from the input of the I/Q vector modulator return out of phase and thus cancel at the circuit input. Therefore, changes in the matching at the input of the vector modulator with different phase shifts makes an insignificant impact on the return loss seen from the input of the Lange coupler.

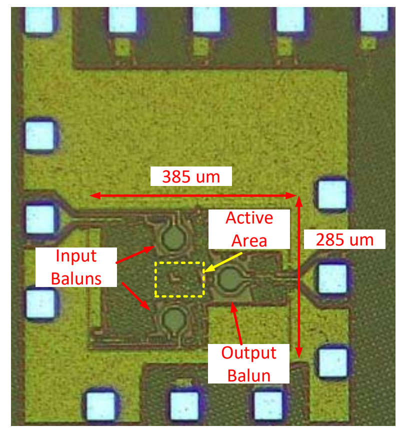

Fig. 4. Microphotograph of the Phase Shifter.

B. I/Q Vector Modulator

The schematic of the IQ vector modulator is shown in Fig. 3. The architecture is based on an active vector multiplier where the weights of the vectors are controlled by the tail current sources. The current sources can be continuously adjusted but for simulation and measurement are set with 3 bit control. Consequently, the phase shifter is implemented with 5 bit control with 2 bits from the I and Q voltages and 3 bits from each of the current sources. The transistors are biased to handle nominal tail currents of up to 8 mA.

III. Measurement Results

The phase shifter is fabricated in GlobalFoundries 45-nm SOI CMOS technology using a trap-rich substrate. The chip microphotograph is shown in Fig. 4 and the chip area is 385 μm $\times$ 285 μm. The measurement is performed using a 67-GHz Keysight N5247A Network Analyzer to measure the S-parameters of the phase shifter from DC to 70 GHz and with W-band frequency extenders to measure between 75-110 GHz. Consequently, there is a 5 GHz gap from 70 GHz to 75

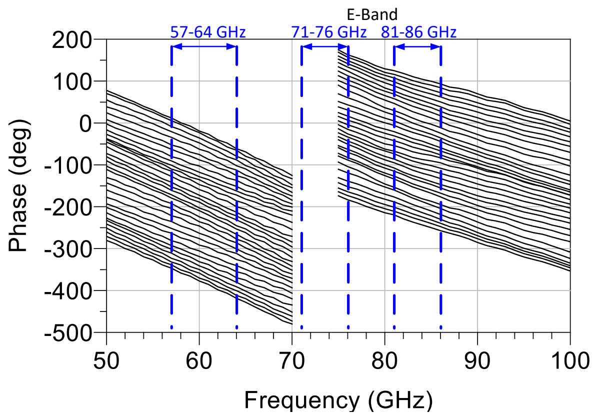

Fig. 5. Measured phase across 50-70 GHz and 75-110 GHz bands.

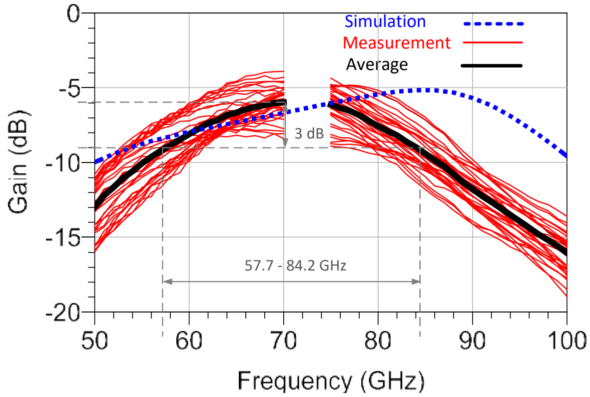

Fig. 6. Measured and average gain across 50-70 GHz and 75-110 GHz bands.

GHz that is not covered by measurements. Nonetheless, the measurements show consistent data that agree with simulation data.

Fig. 5 shows the measured phase over the frequency bands of 50-70 GHz and 75-100 GHz. The phase shifter provides coverage of 360° with 32 different phase states that are measured. The measured insertion loss of the phase shifter is depicted in Fig. 6. The average insertion loss of the phase shifter is 6 dB. Since analog control of the phase shifters is possible, the gain variation could be reduced through current adjustment. A 3-dB bandwidth is measured based on the average gain and is found to be 57.7-84.2 GHz. The input and output matching of the phase shifter are better than -10 dB and -8 dB, respectively, across the same frequency range as shown in Fig. 7 and Fig. 8.

Fig. 9 shows the calculated RMS phase and gain error from measurement data. Over the frequency band of 50-100 GHz, the average RMS phase error is about 7° while the average RMS gain error is less than 1 dB.

Finally, large signal measurements of the phase shifter at 70 GHz are demonstrated in Fig. 10 and indicate input power compression at around 7 dBm. However, the average measured

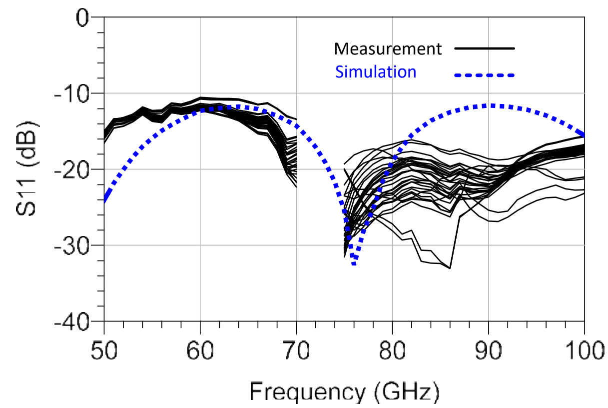

Fig. 7. Measured input matching for 50-70 GHz and 75-110 GHz bands.

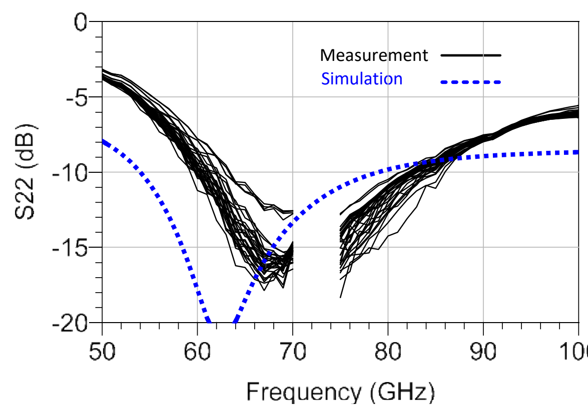

Fig. 8. Measured output matching for 50-70 GHz and 75-110 GHz bands.

OP_{1dB} is -1 dBm at 70 GHz.

A brief table of comparison is shown in Table 1. Compared to other wideband mm-wave phase shifters, this design offers wider bandwidth with the capability to cover all bands from 57 to 86 GHz. Additionally, the input power compression is better than prior wideband phase shifters though it is substantially lower than the simulated result. Finally, the area of the phase shifter is extremely compact and consumes a reasonable amount of power compared to the prior work and relative to the 1-dB compression point.

IV. Conclusion

A wideband 57.7-84.2 GHz active phase shifter implemented in Global Foundry's 45 nm SOI CMOS technology is presented. A compact Lange coupler is used to generate in-phase and quadrature signals over a wide bandwidth. The phase shifter demonstrates high fractional bandwidth compared to other reported works and an average 6 dB insertion loss. The measured average rms phase and gain errors are 7 degrees and 1 dB, respectively. The chip size is 385 μm × 285 μm which is comparabily smaller than other reported works. To the best of authors knowledge, this is the first reported wideband phase shifter that simultaneously covers both 60 GHz band and E-band frequencies.

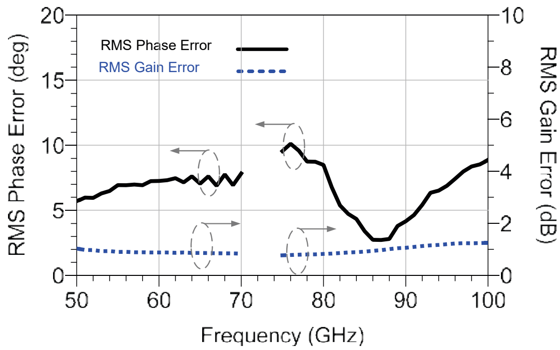

Fig. 9. Measured RMS phase and gain error for 50-70 GHz and 75-110 GHz.

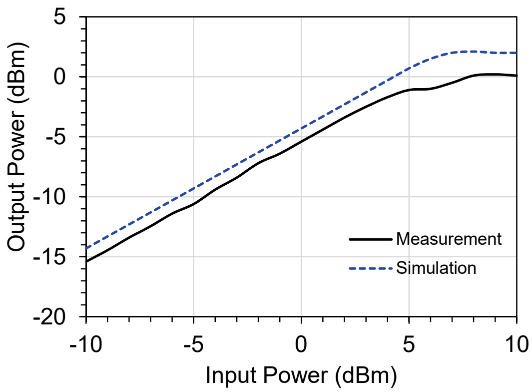

Fig. 10. Simulated and measured output power versus input power at 70 GHz.

TABLE 1
PERFORMANCE COMPARISON OF THIS WORK WITH SIMILAR PUBLISHED WORKS.

Param.\Ref.	[8]	[4]	[9]	[6]	**This Work**
Frequencies (GHz)	57-64	60-80	57-66	78.8-92.8	**57.7-84.2**
Phase Resolution (Bit)	4	4	5	4	**5**
RMS Gain Error (dB)	0.75-1.6	0.6-1.1	0.23	2	**0.8-1.1**
RMS Phase Error (deg)	4.5-10	3.9-10.4	8	11	**2.7-10.1**
Output P_{1dB} (dBm)	-7.9	-23	0.6	-5.7	**-1**
Chip Size (mm^2)	0.61	1.28 (with pads)	0.44	0.17	**0.11**
Power (mW)	19.8	32.4	0	12	**17**
Technology	90 nm CMOS	0.13 μm BiCMOS	65 nm LP CMOS	28 nm CMOS	**45 nm SOI CMOS**

ACKNOWLEDGMENT

The authors acknowledge the support of the NSF Giganets program under Dr. Thyaga Nandagopal and are grateful to Ned Cahoon of GlobalFoundries for access to the 45-nm SOI CMOS process. The authors also thank Prof. Rodwell and Dr. Robert Maurer for helpful discussions on test and measurement. Finally, we recognize the support of Integrand Software for providing access to the EMX tool used for passive modeling.

REFERENCES

[1] S. E. Shih, D. W. Duan, O. Fordham, M. Parmar, K. Tornquist, X. Zeng, P. Chang-Chien, and R. Tsai, “A W-Band 4-Bit Phase Shifter in Multilayer Scalable Array Systems” in *2007 IEEE Compound Semiconductor Integrated Circuits Symposium*, Oct 2007, pp. 1–4.

[2] S. Y. Kim and G. M. Rebeiz, “A 4-Bit Passive Phase Shifter for Automotive Radar Applications in 0.13 um CMOS,” in *2009 Annual IEEE Compound Semiconductor Integrated Circuit Symposium*, Oct 2009, pp. 1–4.

[3] P. J. Peng, J. C. Kao, and H. Wang, “A 57-66 GHz Vector Sum Phase Shifter with Low Phase/Amplitude Error Using a Wilkinson Power Divider with LHTL/RHTL Elements elements,” in *2011 IEEE Compound Semiconductor Integrated Circuit Symposium (CSICS)*, Oct 2011, pp. 1–4.

[4] S. Y. Kim, D. W. Kang, K. J. Koh, and G. M. Rebeiz, “An Improved Wideband All-Pass I/Q Network for Millimeter-Wave Phase Shifters,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 60, no. 11, pp. 3431–3439, Nov 2012.

[5] W. Shin and G. M. Rebeiz, “60 GHz active phase shifter using an optimized quadrature all-pass network in 45nm CMOS,” in *2012 IEEE/MTT-S International Microwave Symposium Digest*, June 2012, pp. 1–3.

[6] D. Pepe and D. Zito, “A 78.8-92.8 GHz 4-bit active phase shifter in 28nm FDSOI CMOS with 2.3 dB average peak gain,” in *ESSCIRC Conference 2015 - 41st European Solid-State Circuits Conference (ESSCIRC)*, Sept 2015, pp. 64–67.

[7] Y.-H. Lin and H. Wang, “A low phase and gain error passive phase shifter in 90 nm CMOS for 60 GHz phase array system application,” in *2016 IEEE MTT-S International Microwave Symposium (IMS)*, May 2016, pp. 1–4.

[8] Y. Yu, K. Kang, C. Zhao, Q. Zheng, H. Liu, S. He, Y. Ban, L. L. Sun, and W. Hong, “A 60-GHz 19.8-mW Current-Reuse Active Phase Shifter With Tunable Current-Splitting Technique in 90-nm CMOS,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no. 5, pp. 1572–1584, May 2016.

[9] D. Huang, L. Zhang, D. Li, L. Zhang, Y. Wang, and Z. Yu, “A 60 GHz 360 5-bit Phase Shifter with Constant IL Compensation Followed by a Normal Amplifier with 1 dB Gain Variation and 0.6 dBm OP-1dB,” *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. PP, no. 99, pp. 1–1, 2017.

[10] S. P. Sah, X. Yu, and D. Heo, “Design and Analysis of a Wideband 15-35-GHz Quadrature Phase Shifter With Inductive Loading,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 61, no. 8, pp. 3024–3033, Aug 2013.