A H-Band Vector Modulator MMIC for Phase-Shifting Applications

D. Müller*, A. Tessmann†, A. Leuther†, T. Zwick* and I. Kallfass‡

*Institute of Radio Frequency Engineering and Electronics, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany
†Fraunhofer Institute for Applied Solid State Physics, 79108 Freiburg, Germany
‡Institute of Robust Power Semiconductor Systems, University of Stuttgart, 70569 Stuttgart, Germany

***Abstract*—This paper presents a H-Band vector modulator which is optimized for phase shifting applications. The vector modulator is realized using a compact topology based on power dividers, baluns and variable gain amplifiers and shows state-of-the-art performance for frequencies between 235 and 270 GHz with very low RMS gain and phase errors. In this frequency range the full 360° phase control range is achieved with less than 6.5 dB insertion loss. The MMIC was fabricated using a 50 nm GaAs mHEMT technology and the resulting chip-size is only 1.25 mm × 1.00 mm.**

***Index Terms*—MMIC, phase shifter, vector modulator, H-Band, GaAs, mHEMT**

I. Introduction

Due to the high absolute bandwidth and the low atmospheric attenuation [1] the millimeter-wave frequency region (30 - 300 GHz) is very attractive for high performance applications such as high speed communication systems or high precision radar applications. There have been several publications in the past years which show fully functional systems at these frequencies [2], [3], [4]. Despite their high integration level these systems lack the capability of antenna beam-steering which would enable the full potential of these systems. In order to enhance such systems with beam-steering capabilities phase shifters are the key components.

Phase shifting can generally be done in the radio frequency (RF), local oscillator (LO) or intermediate frequency (IF) path but direct phase shifting at the RF carrier frequency has several advantages. Phased array systems which employ IF or LO phase shifting necessarily need N frequency conversion chains and therefore at least N mixer circuits, whereby N represents the number of antennas in the array. Usually these mixers need relatively high power levels for driving the LO which is quite challenging at millimeter-wave frequencies. Furthermore due to the use of direct RF phase shifting possible interferes can be suppressed before the signal reaches the mixer, what relaxes the linearity requirements [5], [6].

This paper presents a H-Band vector modulator which is optimized for phase shifting applications. The vector modulator shows very good performance for frequencies between 235 and 270 GHz with very low RMS gain and phase errors and offers the full 360° phase-control range. After presenting the topology of the vector modulator in section II the used technology will be briefly described in section III and the measurement results as well as the evaluation will be presented in section IV.

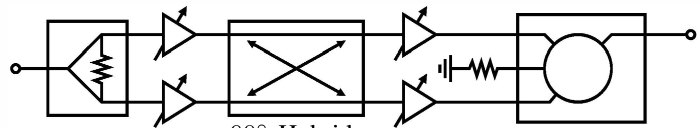

Fig. 1. Simplified schematic of the vector modulator.

II. Circuit Design

Vector modulators are based on the weighted summation of orthogonal vectors which are created out of the input signal. For full flexibility and the later use as phase shifter all four quadrants of the constellation diagram need to be addressed and therefore four orthogonal signal vectors are necessary. For creating these signal vectors a compact topology was chosen which is based on a wilkinson divider, a branchline coupler and a 180° hybrid based on the rat-race topology. The schematic is depicted in Fig. 1. To adjust the magnitude of the orthogonal signal vectors variable gain amplifiers (VGA) in a cascode configuration were chosen. In comparison to adjustable attenuators, which also may be used for adjusting the magnitude, they are compact and minimize the loss of the overall circuit. Special considerations need to be done in terms of the phase versus gain behavior of the VGAs. To realize straight signal vectors the phase versus gain deviation should be as small as possible. This was achieved using a phase compensation capacitance at the gate of the common-gate transistor of the cascode, which was initially proposed in [7]. A layout picture of the MMIC is shown in Fig. 2, the chip-size is only 1.25 mm × 1.00 mm including the RF and DC probing-pads.

III. Technology

The presented vector modulator was manufactured in a 50 nm GaAs mHEMT technology with a f_t of 375 GHz which is grown on 4-inch wafers. The technology was provided by the Fraunhofer Institute for Applied Solid State Physics (IAF). The transistors are embedded in a grounded coplanar waveguide environment (CPWG) with a ground to ground spacing of 14 µm. A 2.7 µm thick galvanic metal layer is utilized to realize metal-insulator-metal (MIM) capacitors, airbridges and bond-pads. After the front-side processing the wafers are thinned to 50 µm and through substrate vias are etched from the backside and metalized. These vias are essential for substrate wave suppression and providing a good ground potential to the front

978-1-4799-8275-2/15/$31.00 ©2015 IEEE

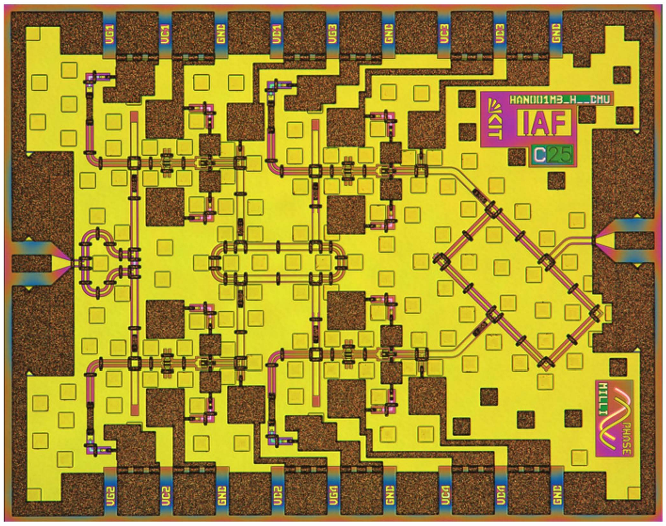

Fig. 2. Chip photography of the presented H-Band vector modulator. The chip has a total size of $1.25\,\text{mm} \times 1.00\,\text{mm}$.

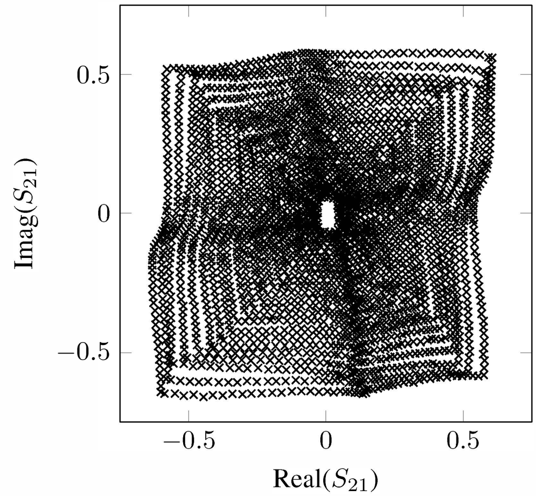

Fig. 3. Measured constellation diagramm of the vector modulators S_{21} at 255 GHz for 4200 different bias voltages.

side of the circuits. Additional information about the applied process can be found in [8].

IV. Measurement Results

The fabricated MMICs S-parameters were measured using an on-wafer setup employing a Keysight N5247A PNA-X with WR-03 OML. Inc. extension modules. The chip was biased using a National Instruments multi-channel Source-Measure-Unit at 2 V drain voltage and gate voltages between -0.3 V and 0.15 V. The maximum gate control voltage sweep step width was 10 mV and the maximum dc power consumption was 13.7 mW. In Fig. 3 the measured S_{21} parameter in real- and imaginary-part is shown for a frequency of 255 GHz. As can be seen the constellation diagram almost forms a square with only very little deviation. This verifies the successfully compensated phase versus gain deviation of the used VGAs. For the subsequent evaluation 16 phase-states with a difference of $22.5°$ were extracted out of the constellation diagram what represents the phase-states of a 4 bit phase shifter. The magnitude of S_{21} versus frequency for these 16 phase-states is depicted in Fig. 4, showing that the magnitude is between -3.5 dB and -6.5 dB between 240 and 270 GHz. The corresponding phase curves are shown in Fig. 5 and show a good broadband behavior.

In general the vector modulator topology allows to minimize the gain and phase error for one certain frequency to almost zero depending only on the accuracy of the control voltages. This might be used for high precision narrow band applications but is not an adequate measure for broadband applications. For a better insight of the vector modulators broadband performance the RMS values for gain- and phase-error versus frequency were calculated and are depicted in fig 6. By using the zero state as reference, it can be observed that the RMS gain-error is less than 3 dB over the full frequency range from 220 to 290 GHz. The RMS phase-error limits the resolution

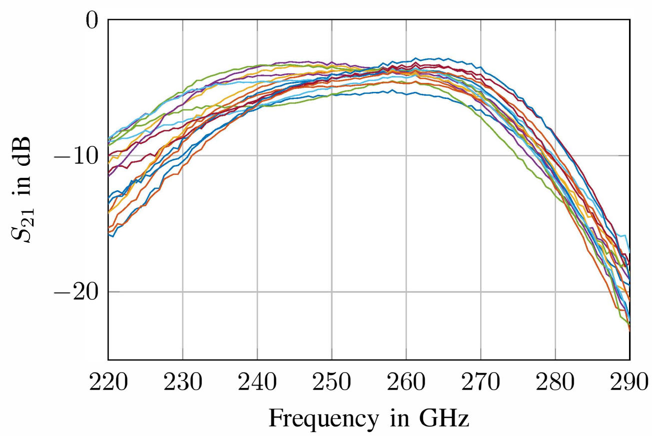

Fig. 4. Measured magnitude of S_{21} in dB for the extracted 4 Bit phase-states.

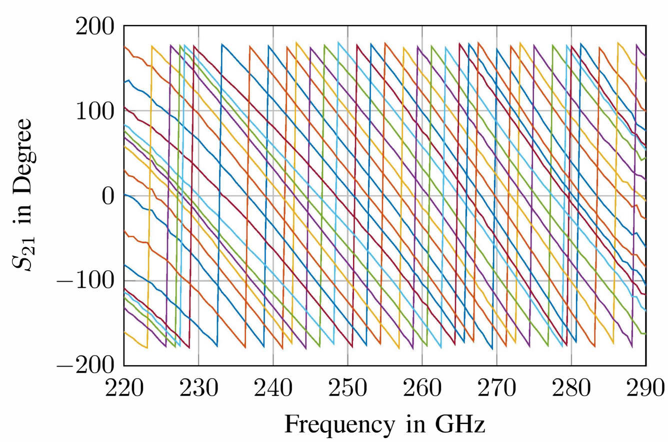

Fig. 5. Measured phase of S_{21} for the extracted 4 Bit phase-states.

978-1-4799-8275-2/15/$31.00 ©2015 IEEE

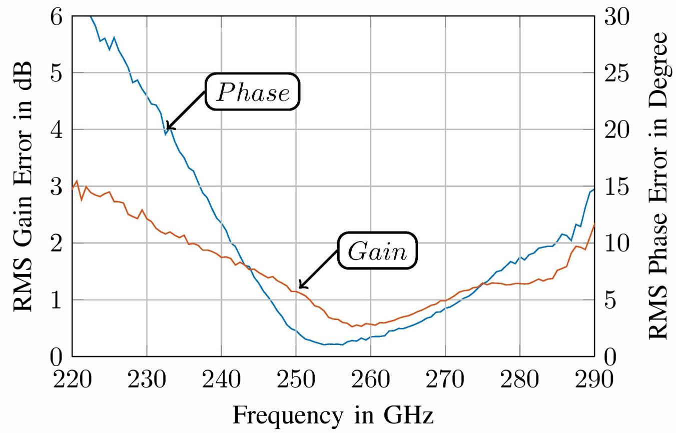

Fig. 6. Measured RMS gain and phase error for the extracted 16 phase-states.

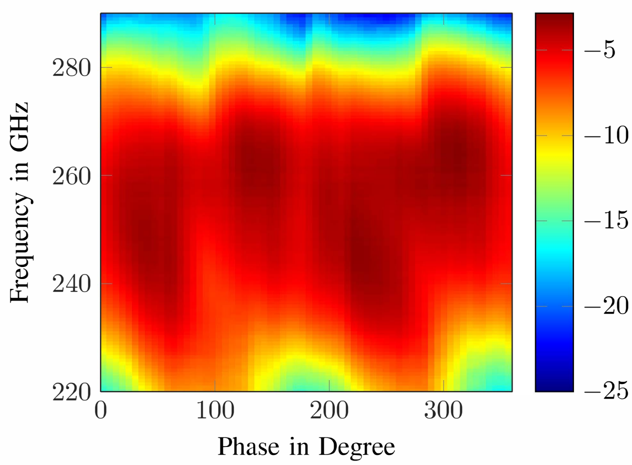

Fig. 7. Measured Gain/Phase in degree plot for frequencies between 220 and 290 GHz. The unit of the color-bar is held in decibel.

and usable frequency range of the phase shifter. A common measure for the usability of a phase shifter is the frequency range where the RMS phase error is smaller than the half step width of the lowest bit. In the case of a 4 bit phase shifter the half of the lowest bit equals 12.5° what limits the usability of the presented vector modulator to frequencies between 240 and 290 GHz. For a good overview of the overall performance the gain/phase behavior is plotted versus frequency in Fig. 7. This plot shows the amplitude versus frequency behavior for all possible phase-states between 0° and 360°. It can be observed that the vector modulators offers excellent performance for the full 360° phase control range with only very little amplitude and bandwidth deviation between the different phase-states. The comparison of this work with other recently published vector modulators is done in Table I and shows that this work is the highest frequency realization of a 360° vector modulator while maintaining or outperforming its lower frequency competitors in key characteristics such as average gain, RMS gain- and phase-error or DC power consumption.

V. Conclusion

The presented vector modulator shows state-of-the-art performance regarding the key characteristics in gain and phase behavior. In the frequency range from 240 to 270 GHz the evaluated 16 phase-states, which are equal to a 4 Bit phase shifter, achieved a RMS gain and phase error of less than 1.8 dB and 12.5°, respectively. These results confirm that vector modulators are a very good choice as phase shifting elements in future phased array systems.

Acknowledgment

We express our gratitude to our colleagues in the IAF technology department for their excellent contributions during epitaxial growth and wafer processing. This work was supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) in the framework of the MilliPhase project.

References

[1] R. Emery and A. M. Zavody, "Atmospheric propagation in the frequency range 100-1000 GHz," *Radio and Electronic Engineer*, vol. 49, no. 7.8, pp. 370–380, July 1979.

[2] F. Boes, J. Antes, T. Mahler, U. Lewark, D. Meier, T. Messinger, R. Henneberger, A. Tessmann, T. Zwick, and I. Kallfass, "Experimental validation of adverse weather effects on a 240 ghz multi-gigabit wireless link," in *Microwave Symposium (IMS), 2014 IEEE MTT-S International*, June 2014, pp. 1–3.

[3] T. Jaeschke, C. Bredendiek, and N. Pohl, "A 240 ghz ultra-wideband fmcw radar system with on-chip antennas for high resolution radar imaging," in *Microwave Symposium Digest (IMS), 2013 IEEE MTT-S International*, June 2013, pp. 1–4.

[4] H.-J. Song, J.-Y. Kim, K. Ajito, M. Yaita, and N. Kukutsu, "Fully integrated ask receiver mmic for terahertz communications at 300 ghz," *Terahertz Science and Technology, IEEE Transactions on*, vol. 3, no. 4, pp. 445–452, July 2013.

[5] S. Alalusi and R. Brodersen, "A 60ghz phased array in cmos," in *Custom Integrated Circuits Conference, 2006. CICC '06. IEEE*, Sept 2006, pp. 393–396.

[6] K.-J. Koh and G. Rebeiz, "0.13- um cmos phase shifters for x-, ku-, and k-band phased arrays," *Solid-State Circuits, IEEE Journal of*, vol. 42, no. 11, pp. 2535–2546, Nov 2007.

[7] F. Ellinger, U. Jorges, U. Mayer, and R. Eickhoff, "Analysis and compensation of phase variations versus gain in amplifiers verified by sige hbt cascode rfic," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 57, no. 8, pp. 1885–1894, Aug 2009.

[8] A. Leuther, A. Tessmann, M. Dammann, C. Schworer, M. Schlechtweg, M. Mikulla, R. Losch, and G. Weimann, "50 nm MHEMT Technology for G- and H-Band MMICs," in *Indium Phosphide Related Materials, 2007. IPRM '07. IEEE 19th International Conference on*, 2007, pp. 24–27.

[9] 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," in *Compound Semiconductor Integrated Circuit Symposium (CSICS), 2011 IEEE*, Oct 2011, pp. 1–4.

[10] P.-S. Wu, H.-Y. Chang, M.-F. Lei, B.-J. Huang, H. Wang, C.-M. Yu, and J. Chern, "A 40-74 ghz amplitude/phase control mmic using 90-nm cmos technology," in *Microwave Integrated Circuit Conference, 2007. EuMIC 2007. European*, Oct 2007, pp. 115–118.

[11] M. Elkhouly, S. Glisic, F. Ellinger, and J. C. Scheytt, "120 ghz phased-array circuits in 0.25 um sige bicmos technology," in *Microwave Conference (GeMiC), 2012 The 7th German*, March 2012, pp. 1–4.

[12] M. Elkhouly, S. Glisic, C. Meliani, F. Ellinger, and J. Scheytt, "220 - 250-ghz phased-array circuits in 0.13-/spl mu/m sige bicmos technology," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 61, no. 8, pp. 3115–3127, Aug 2013.

[13] H. Yu, K. Lee, and M. Kim, "300 ghz vector-sum phase shifter using inp dhbt amplifiers," *Electronics Letters*, vol. 49, no. 4, pp. 263–264, Feb 2013.

Reference	[9]	[10]	[11]	[12]	[13]	This Work
Technology	90 nm CMOS	90 nm CMOS	0.25 µm SiGe BiCMOS	0.13 µm SiGe BiCMOS	250 nm InP DHBT	50 nm GaAs mHEMT
Phase-Control	360°	360°	360°	360°	90°	360°
Frequency	57 - 66 GHz	40 - 74 GHz	110 - 130 GHz	220 - 245 GHz	300 GHz	240 - 270 GHz
Avg. Gain	-4 dB	-18 dB	-10 dB	-6 dB	9.1 dB	-4.5 dB
RMS Gain Error	$<$0.52 dB	N/A	N/A	$<$1 dB	N/A	$<$1.8 dB
RMS Phase Error	$<5.1°$	N/A	N/A	N/A	N/A	$<12.5°$
DC Consumption	15.6 mW	30 mW	N/A	10.5 mW	N/A	13.7 mW
Chip Area (mm^2)	0.70 x 0.45	0.70 x 0.60	N/A	N/A	0.75 x 0.50	1.25 x 1.00

TABLE I
PERFORMANCE COMPARISON OF THIS WORK WITH OTHER RECENTLY PUBLISHED MMW VECTOR MODULATORS.

978-1-4799-8275-2/15/$31.00 ©2015 IEEE