A linear 70-95 GHz differential IQ modulator for E-band Wireless Communication

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Abstract— **In this paper, a direct IQ modulator MMIC with a novel differential architecture, for high speed E-band wireless communication is presented. The IQ modulator consists of two balanced resistive mixer cells, on-chip marchand balun and differential branchline coupler for quadrature LO signal generation. When operating as a single side band mixer, it shows conversion loss of 11 dB and side-band suppression higher than 20 dB. LO to RF isolation and OIP3 have been measured to be more than 30 dB and 13 dBm respectively, throughout the E-band. To the authors' best knowledge this is the first presented resistive IQ-modulator suitable for the full E-band.**

Index-terms; E-band, IQ, modulator, SSB mixer, single side-band, Resistive mixer, MMIC, mHEMT, GaAs, differential

I. Introduction

In October 2003 the Federal Communications Commission (FCC) released 13 GHz of yet unused spectrum in the frequency bands 71-76, 81-86, and 92-95 GHz, dedicated for high speed wireless communications in the United States [1]. The two former bands are now usually referred to as the E-band. By now, many countries have followed FCC's example by licensing the E-band for communication purposes. The E-band has attracted a lot of interest because its possibility to achieve multi-Gb/s data rates in full duplex even with simple binary modulation. Since the release six years ago of the E-band, many radio manufactures are still using on-off keying due to the high bandwidth available. Over the past few years data traffic in the wireless mobile networks has increased continuously, reaching the maximum capacity of today's microwave backhauls. Thus, the prospects for the E-band to become the next generation of point-to-point microwave backhaul links look very promising. The market for E-band point-to-point links is at take-off and mobile operators are eager for higher speeds in their backhauls to offer customers more speed. In spite of this emerging challenge, little has been published on this subject.

To improve spectral efficiency and speed an IQ modulator that supports multiple modulation formats must be used. For complex n-level Quadrature Amplitude Modulation schemes (QAM), linearity in such a modulator is essential. The IQ modulators that so far have been published above 60 GHz are based on reflection type phase shifters and a Gilbert cell mixer [2], [3], [4]. While the former often have low conversion loss, they suffer from poor linearity and often require bias to tune the phase of the reflection. IQ modulators based on resistive mixers are reported at 60 GHz but not higher [5], [6]. In this paper, an IQ modulator using balanced resistive mixer cells designed with a novel differential methology for GaAs MMICs, including a Differential Branchline Coupler (DBC) is presented.

II. Circuit Design

The IQ-modulator is implemented in a GaAs 0.15 µm gate length mHEMT (metamorphic high electron mobility transistor) technology from WIN semiconductors, Taiwan. The simplified schematic representation of the modulator is shown in Figure 1 and the layout in Figure 2 respectively.

The modulator consists of two balanced resistive mixer cells [7]. Each mixer cell consists of two 2×50 µm transistors connected to a common source. Input signals are IQ, $\overline{IQ}$, and a single ended LO. The differential quadrature LO signals are formed on chip by a Marchand balun [8] followed by a (DBC). Due to symmetry imperfections in the DBC, differential to common mode transformation occurs. To improve the common mode rejection ratio, a loop that shorts the common mode signal is used after the DBC. The mixing product of these generates a single ended RF which is extracted at the drain terminals of the mixer cell. Because of the balanced mixer cell both LO and IF will be isolated from the RF-port. The IQ signals utilize a low pass filter to block the RF and LO signals from the IF port [9]. Finally, Wilkinson combiners sum up the RF signals and at the same time block all differential signals from that port.

In a modulator the phase and amplitude balance are of uttermost importance to achieve low Error Vector Magnitude (EVM). Either differential quadrature signals can be applied at the gate terminals by a pumping LO or collected at the drain terminals as a small signal RF. To achieve better EVM the former solution is preferred since the amplitude difference are of less importance in this state, phase is however equally important.

One of the key components in this circuit is the DBC and as already mentioned a modulator requires high amplitude and phase balance to have low EVM. The advantage of using a differential hybrid compared to a conventional hybrid in this technology is the difference in reference planes. In a conventional hybrid, with its Δ-port terminated with 50 Ω through a backvia to ground, that backvia will introduce a considerably large inductance at these frequencies and must be accounted for. In a differential circuit that termination has no parasitic inductance. Another important aspect is the reduction of either one hybrid or balun otherwise needed to provide the differential quadrature signals.

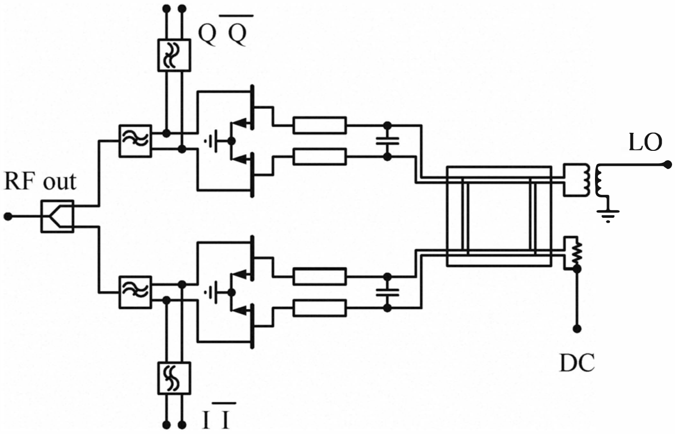

Figure 1. Schematic representation of the IQ modulator.

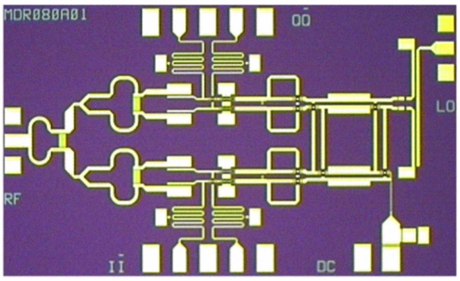

Figure 2. Chip photo of the IQ modulator MMIC. The chip size measures 2.5×1.5 mm^2.

III. Measurement Setup

The measurements have been carried out on wafer using GSG-probes for the LO and RF ports and GSGSG for the IQ ports. For the signal generation of IQ and $\overline{IQ}$ Agilent's PSG signal synthesizers 8247C and 8257C in addition with external 90° and 180° hybrids were used. An HP 83650A synthesizer together with mm-wave modules HP83558A and HP83557A were used to produce the LO signal. Finally an HP 8565EC spectrum analyzer with harmonic mixers HP 11974V and 11970W were used to measure the frequency components at the RF port. All losses up to probe tips have been calibrated for. Phase/amplitude imbalance from the external hybrids has not been calibrated for.

IV. Measurement Results

Conversion loss (CL) and side-band suppression (SBS) have been measured over a frequency span from 60 GHz to 100 GHz with an IF span from 1 GHz to 12 GHz. During the two-tone power measurement both LO and IF input power were swept at some fixed frequency points.

In Figure 3 the CL and SBS are plotted. CL is smooth at 11 dB and SBS is higher than 20 dB from 70-95 GHz.

In Figure 4, the LO is fixed in the center of the three E-band frequency windows while sweeping the IF from -2 to 2 GHz. When the IF is negative, the side-band is measured on the Upper Side Band (USB) and RF on the Lower Side Band (LSB). When positive, the side-band is measured on the LSB side and RF on the USB, therefore the RF and sideband are on top of each other.

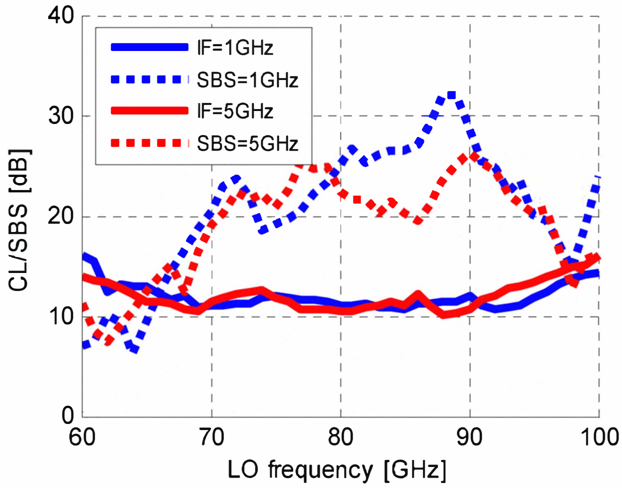

Figure 3. Conversion loss and side-band suppression over a swept LO-frequency from 60 to 100 GHz at two fixed IF frequencies of 1 and 5 GHz. LO power is fixed at 8 dBm.

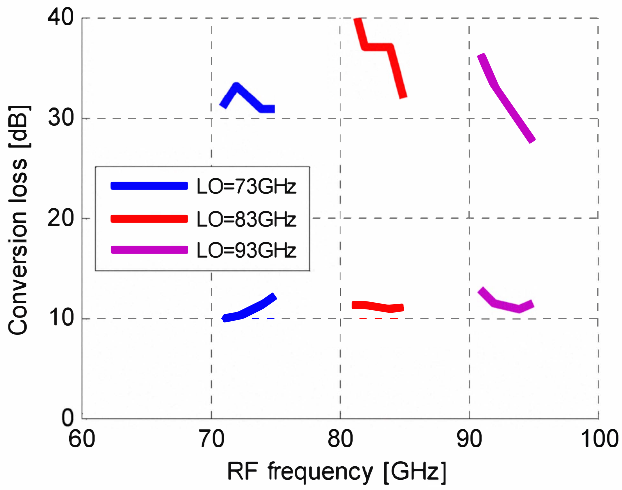

Figure 4. Conversion loss for both LSB and USB at three fixed LO frequencies and IF between -2 and 2 GHz.

In Figure 5 the CL is plotted vs. LO power. At mm-wave frequencies, frequency generation and especially power can be an issue. At a power level of 5 dBm the IQ modulator still performs well with respect to CL. In Figure 6 a two-tone measurement is performed at an LO power of 13 dBm. Output P1dB and OIP3 are measured to be 0 dBm and 13 dBm respectively. In Figure 7 the OIP3 point is measured with respect to LO power. While increasing LO power, the linearity of the modulator increases linearly. At the highest LO power of 13 dBm, the OIP3 was measured to be 13 dBm.

Finally in Figure 8 the LO to RF isolation is shown and is better than 30 dB across the whole band.

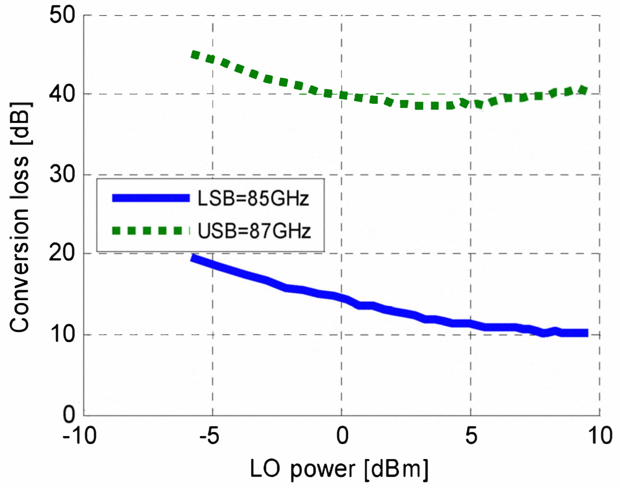

Figure 5. Conversion loss vs. input LO power. IF frequency and input power is 1 GHz and -10 dBm respectively.

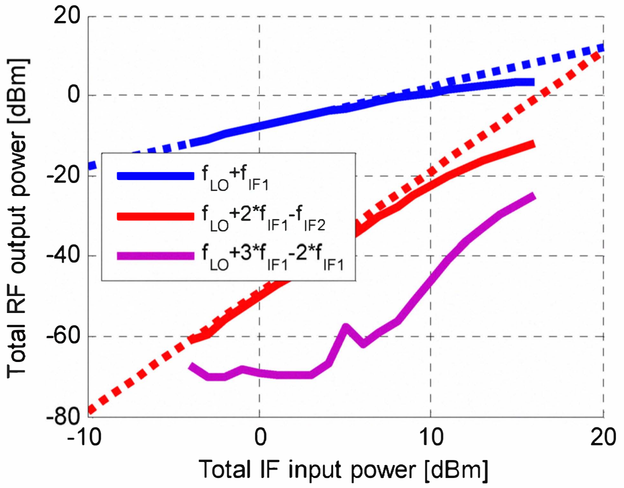

Figure 6. Two tone measurement with f_{IF1}=1010 MHz and f_{IF2}=990 MHz. Three mixring products are shown, IM1, IM3 and IM5. The latter diminishes into the noise floor at the lower input power levels. LO power level is 13 dBm and frequency is 83.5 GHz.

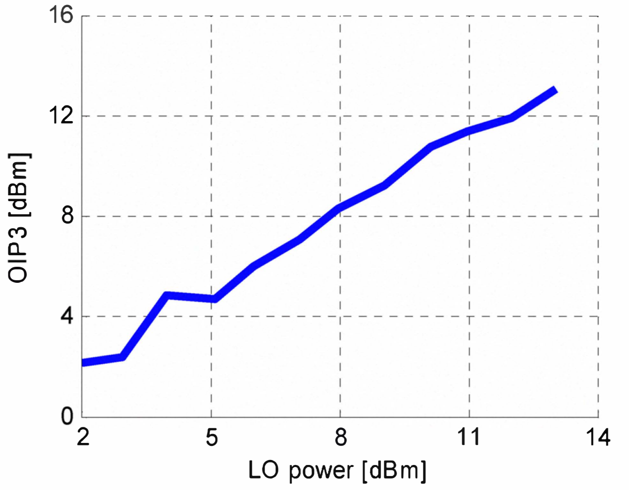

Figure 7. OIP3 vs. LO power. LO and IF frequencies are 83.5 and 1 GHz respectively.

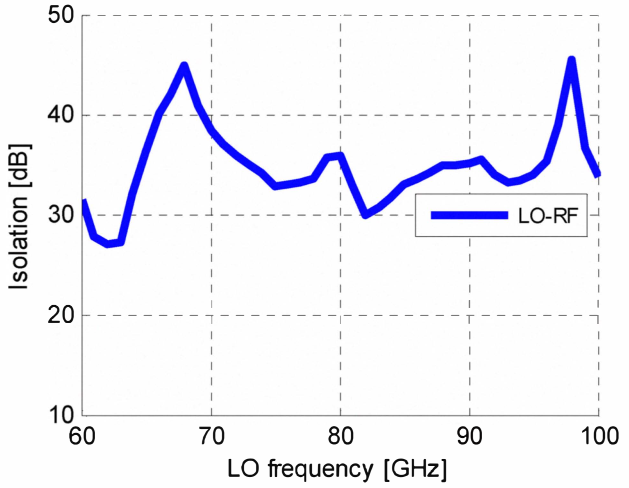

Figure 8. LO to RF isolation.

V. Summary And Comparison

A summary of the key parameters is found in TABLE I together with a handful relevant IQ modulators [2-6]. Since very few publications can be found regarding E-band IQ modulators also IQ modulators at closely related frequencies are incorporated in the comparison.

The IQ modulator presented in this paper show the overall best performance. It features broadband, smooth conversion loss and high side-band suppression. The IQ modulator also reports a high OIP3 of 13 dBm and an output P1dB of 0 dBm without an output buffer amplifier, which was used in [4].

TABLE I. SUMMARY AND COMPARISON WITH OTHER MODULATORS

Ref	*[2]*	*[3]*	*[4]*	*[5]*	*[6]*	*This Work*
Frequency [GHz]	50-110	30-70	77	55-66	57-66	70-95
Sideband suppression [dBc]	>21	>10	>28	>24	>19	>20
LO to RF isolation [dB]	>23	n/a	>23	>25	>35	>30
LO power [dBm]	-8	n/a	2-6.5	0	8	5-13
Conversion loss [dB]	13±5	10±3	n/a	11±0.5	14±1.5	11±0.5
Power consumption [mW]	20	0	500	0	0	0
Output P1dB [dBm]	n/a	-5	2.5	-5.6	-13	0
OIP3 [dBm]	n/a	n/a	n/a	n/a	4	13
Chip size [mm^2]	2×2	1×1	1.5×0.9	2.5×1.15	1.5×1.5	2.5×1.5
Process	1 µm GaAs HBT	0.5 µm E/D pHEMT	SiGe HBT	0.15 µm MOD-FET	0.25 µm pHEMT	0.15 µm mHEMT
Type	Reflection based phase shifter	Reflection based phase shifter	Gilbert cell	Double balanced Resistive mixer	Single balanced resistive mixer	Single balanced resistive mixer

VI. CONCLUSION

This paper has shown a successful implementation of a direct IQ modulator in 0.15 µm mHEMT GaAs technology for the E-band (71-76, 81-86 and 92-95 GHz). The IQ modulator has a measured conversion loss of 11 dB, sideband suppression of more than 20 dB, LO to RF isolation higher than 30 dB and OIP3 of 13 dBm. The broadband, smooth conversion loss, high side-band suppression and high linearity makes this IQ modulator very well suited for E-band RF-frontends. To the authors' best knowledge, this is the first resistive IQ modulator that covers the entire E-band.

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