A Direct Ku-Band Linear Subharmonically Pumped BPSK and I/Q Vector Modulator in Multi-Layer Thin-Film MCM-D

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***Abstract* — A direct Ku-band linear subharmonically pumped BPSK and I/Q vector modulator has been developed using multi-layer thin-film MCM-D technology. All passives are integrated in the low cost MCM-D substrate. The subharmonic mixing is performed using a beam-lead anti-parallel diode pair, mounted onto the MCM using thermocompression. No tuning has been performed on the circuits. The BPSK modulator has a very flat mixer conversion due to an optimal harmonic loading of the third harmonic of the LO: measurements show a +/- 0.25 dB variation on the conversion loss for an LO-frequency varying between 6.8-7.6 GHz. The LO and RF return loss are below -14 dB and -12.5 dB respectively. The I/Q vector modulator consists of a Wilkinson power divider, a CPW Lange coupler and 2 BPSK modulators. The LO and RF return loss are better than -13 dB and -18 dB respectively. The QPSK-modulator has a measured image rejection better than -27 dB over the RF-range of 13.4-15.2 GHz band (corresponding to a vector phase and amplitude error lower than 2° and 1%). The image rejection is even better than -32 dB over the VSAT band (RF: 14-14.5 GHz).**

I. Introduction

Zero-IF or direct digital modulation at microwave frequencies has gained considerable interest for some years now, due to the simplicity and compactness of the transmitter [1-3]. Compared to modulation schemes using one or more IF frequencies, it offers several advantages such as a reduction in power consumption, board space and hardware (upconvertors and filters) and the achievement of high modulation bandwidths. Typical applications are found in satellite transmission with on-board signal processing and microwave digital radio links.

Sub-harmonic mixing is attractive due to the inherent LO/RF isolation. For mixing at an even harmonic of the LO, sub-harmonic mixers (SHM) typically use a nonlinear device with an antisymmetric current-voltage characteristic such as an antiparallel Schottky barrier diode pair.

Recent realisations primarily use GaAs MMIC technology [1-3] which results in an expensive solution. Moreover, only a small part of the chip-area is consumed by the active devices such as buffer transistors and diodes. Another, more cost-effective solution is to use multilayer thin-film multi-chip module technology (MCM-D). It offers a very high reproducibility of small dimensions and is, therefore, a promising technology for the low-cost integration of RF and microwave circuits. Traditionally, MCM-D has been developed as a high performance packaging and interconnect technology. With the availability of high performance integrated passives, a high degree of integration can be obtained hereby reducing size, weight, but also cost and power consumption as compared to previous hybrid solutions. Up to now, integrated passives have primarily been focussed towards passive applications at lower microwave frequencies, however, they can also be used for the realization of more complex microwave circuits. This will be demonstrated in this paper by the design of a Ka-band BPSK and QPSK modulator. To the author's knowledge, this is the first modulator integrated in MCM-D

II. MCM-D Technology

IMECs MCM-D layer built-up (Fig. 1) consists of alternating thin layers of BCB ($\tan\delta \approx 5.10^{-4}$; $\varepsilon_r = 2.65$) and low loss copper metallisations deposited on a borosilicate glass carrier substrate ($\varepsilon_r = 6.2$, $\tan\delta \approx 9.10^{-4}$).

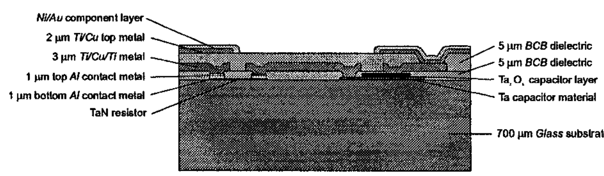

Fig. 1: Layer built-up of IMEC's MCM-D technology

A coplanar waveguide design methodology is used. The standard CPW line is located on the middle low-loss Cu metal layer (the bottom and top metallization layers can also be used). Typical losses are -0.07 dB/mm at 20 GHz for the standard 50 Ω line (width 77 µm, slot 20 µm). TaN-resistors with a typical value of 25 Ω/□ are available. For the larger capacitance values, anodised tantalum (720 pF/mm²) is used whereas for the small capacitors (4.7 pF or 9.4 pF/mm², depending on the type) BCB is used as insulating dielectric. The quality factors of the inductors may go above 100 at 10 GHz (inductances < 1.7 nH). Naturally, for larger inductances a lower quality factor will be obtained due to the increased losses and capacitive coupling between the turns. However, an inductor of 18 nH still has a maximum Q of 38 at 2 GHz while a 40 nH inductor still has a Q of 29 at 1 GHz. All passive components and discontinuities have been modelled and integrated in a design library. More information on the models and the technology can be found in [4-6].

III. BPSK Modulator

The I/Q linear vector modulator has been developed for VSAT applications (RF: 14-14.5 GHz; sub-harmonic LO: 7-7.25 GHz). The design band of the modulators was taken in the range 13.6-14.9 GHz.

A. Design

The mixer uses an anti-parallel diode pair (APDP) mounted in a shunt-to-ground configuration in combination with a triplexer structure. We have used the HSCH-9251. The architectural implementation of the triplexer is shown in Fig. 2. The requirements on the IF and RF-filter are only moderate due to the presence of the LO-block filter. The IF-filter is a 4th order low-pass filter, providing an open at the RF-frequency. The RF-filter is a 3rd order high-pass filter, providing an open at the IF-frequency.

L_{shunt} is a $\lambda/4$ transmission line at 7.1 GHz which provides a short at point B for the LO and the third harmonic. L_{series} can be tuned in combination with the LO-filter, to provide an optimal third harmonic termination at point A while at the same time matching the diode at the LO-frequency. Other requirements for the LO-filter are to provide an open at the RF and IF frequencies.

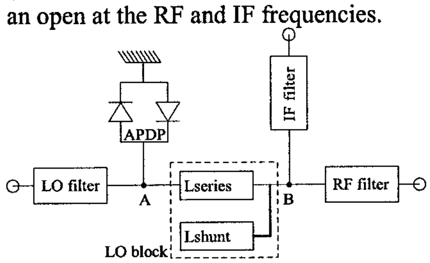

Fig. 2: Architectural implementation of the BPSK modulator.

The LO-filter has been realized as a 4th order low pass (LP) filter cascaded by a 3rd order high pass filter as this allowed to simultaneously fulfill all constraints. Due to the LP filter structure, the harmonic termination at point A is well defined and is not influenced by the impedances presented by the circuits cascaded with the modulator. The incorporated LP filter further offers embedded filtering for the second harmonic of the VCO's output spectrum.

The resulting BPSK modulator requires 10 dBm LO-power and consumes 3.3 x 14.1 mm^2.

B. Measurements

The measured versus simulated conversion loss as a function of LO-frequency is given in Fig. 3. An excellent agreement can be observed which indicates the high quality of the models. A very flat behavior (-10.8 +/- 0.3) dB is obtained due to the correct harmonic loading of the third harmonic of the LO [7]. The measured phase balance (using a non-linear network measurement system) is shown in Fig. 4: over the 13.0-15.2 GHz band, the phase balance is nearly perfect and equals (180 +/- 0.5)°. This is due to the good current-voltage characteristics of the APDP. The LO return loss is better than -14 dB over the 6.8-7.6 GHz band while the RF return loss is better than -12.5 dB over the 13.6-15.4 GHz band.

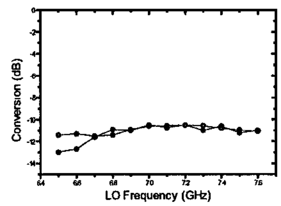

Fig. 3: Measured (•) versus simulated (o) conversion loss as a function of LO-frequency.

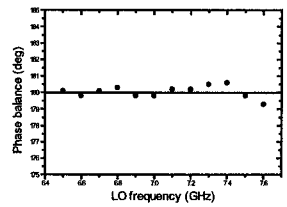

Fig. 4: Measured phase balance of the BPSK modulator.

The modulator has a maximum linear output power of -10 dBm (in each sideband) with the harmonics of the modulating frequency remaining below -31 dB. The suppression of the LO-fundamental is -30 dB at the ouput (-20 dBm) while the second harmonic of the LO is more than -40 dB below the BPSK signal. The corresponding output spectrum is shown in Fig. 5.

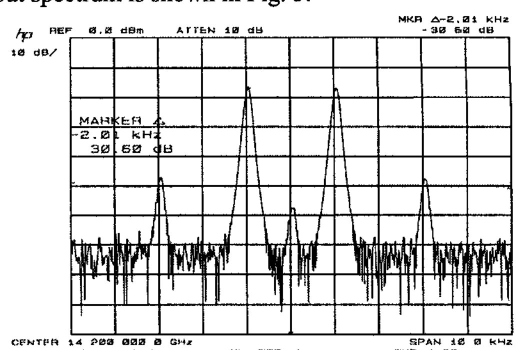

Fig. 5: Measured output spectrum of the BPSK modulator: a linear output power of -10 dBm per sidelob is possible with the harmonics of the modulating frequency below –31 dB.

When the modulator is used in a system, the second harmonic of the VCO should be suppressed. This is also performed by the LO-filter having a measured -22 dB suppression of the second harmonic of the LO.

IV. I/Q VECTOR MODULATOR

The chip was designed to perform QPSK modulation, however, as it is a linear vector modulator, any digital modulation scheme can be implemented.

The modulator is obtained by combining 2 BPSK subharmonic modulators, a Wilkinson power divider and a quadrature coupler. The Wilkinson splits the LO-power and isolates the BPSK-modulators. The quadrature coupler is used for the summation of the output of the BPSK-modulators hereby providing 90° phase shift. It also isolates both BPSK modulators. A Lange coupler has been selected due to its good isolation, amplitude and phase balance.

Tunable on-chip phase-shifters and buffer amplifiers [2,3] (to increase the isolation between the APDPs) have not been added. This tightens the requirements on the Lange coupler's return loss and isolation but also on the BPSK RF return loss. However, the resulting I/Q vector modulator does not require any DC bias and can be realised with a minimum number of external components.

A. Passive circuits

Over the 6.5-7.6 GHz band, the Wilkinson power divider has a measured return loss better than –22 dB, an isolation better than -25 dB with only -0.33 dB losses. The design-method for the CPW Lange couplers has been outlined in [8, 9]. In the 10.5-14.5 GHz band, the Lange coupler has a measured return loss and isolation better than -20 dB, an amplitude balance below 0.2 dB and a phase balance of (90 +/- 1)°. A low insertion loss of -0.35 dB has been obtained. This can be attributed to the Cu-metallizations and the low-loss dielectrics.

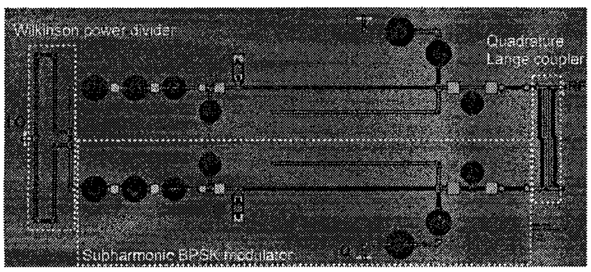

Fig. 6: Picture of the developed I/Q vector modulator.

B. Design

Due to the finite isolation of the Lange coupler and the finite RF return loss of the BPSK modulators, small phase imperfections occur in the resulting QPSK constellation. This has been compensated by cascading a short high and low impedance line with the top and bottom BPSK modulator. Also the terminating impedance of the Lange coupler's 4th port was optimized to obtain a perfect amplitude and phase balance. A picture of the developed QPSK modulator is shown in Fig. 6. The circuit measures 7.6 x 16.9 mm^2.

C. Measurements

As each BPSK modulator is pumped with 10 dBm, the total required LO-power for the I/Q vector modulator is 13 dBm. At the output, the fundamental is more than -30 dB lower over the entire design band.

Both spectral as constellation measurements have been performed.

The measurement of the single sideband (SSB) spectrum is very useful for the characterisation of the modulator as it directly reveals the rejection of all undesired frequency components and circuit imperfections: carrier, image (due to quadrature imperfections) and in-band spurious responses (due to non-linearity of the modulation) [3]. For this purpose, an orthogonal I and Q signal are applied to the modulator. The measured SSB output spectrum is shown in Fig. 7 (LO=7.1 GHz): a maximum linear output power of -10 dBm is possible (harmonics of the modulating frequency below –34 dB). The measured image rejection is -34 dB, while the carrier suppression (2xLO) is -43 dB.

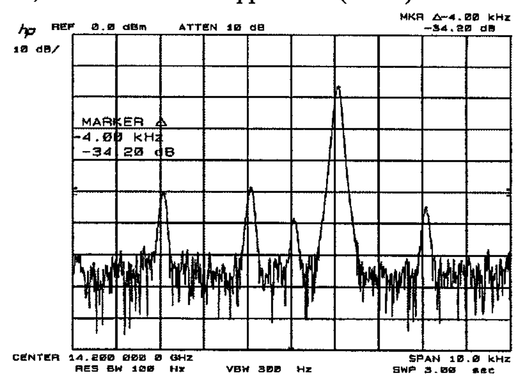

Fig. 7: Measured single sideband output spectrum: a linear output power of -10 dBm is possible with the harmonics of the modulating frequency below –34 dB.

The image rejection has also been measured as a function of LO-frequency (Fig. 8): in the design band, the image rejection is better than –28 dB while in the VSAT-band, the image rejection is even better than -32 dB. It should be emphasized that this result has been obtained without any on- or off-chip amplitude or phase tuning.

Constellation measurements have been performed which confirm the previous results. The measured vector amplitude and phase error are given in Fig. 9: the vector phase error remains below 2° and 0.2 dB over the 6.7-7.6 GHz band. The low vector amplitude and phase error result in a nearly perfect constellation as can be seen in Fig. 10.

The LO return loss of the modulator is better than -13 dB while the RF return loss is better than –18 dB. The flatness of the output spectrum is somewhat lower than for the BPSK modulator due to the presence of the Lange coupler, however, the conversion loss is still in the range of (-14 +/- 0.5) dB over the 6.8-7.5 GHz LO-band.

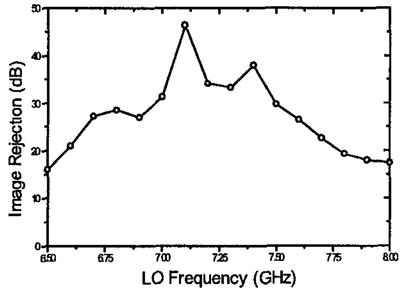

Fig. 8: Measured Image rejection (-o-) as a function of LO-frequency.

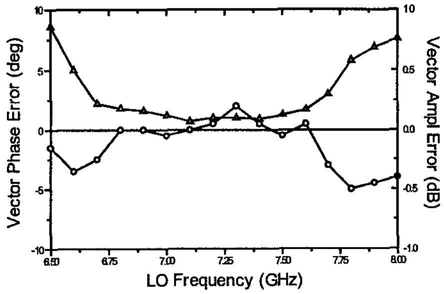

Fig. 9: Measured vector phase (-Δ-) and amplitude (-o-) error as a function of LO-frequency.

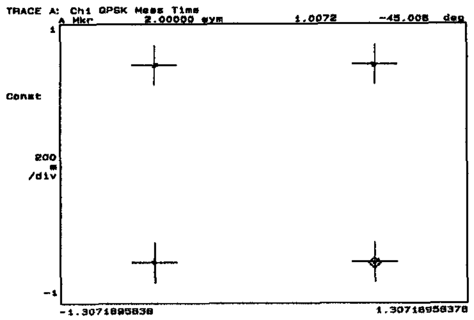

Fig. 10: Measured QPSK constellation: a nearly perfect constellation can be observed.

CONCLUSIONS

A direct Ku-band linear subharmonically pumped BPSK and I/Q vector modulator have been developed using multi-layer thin-film MCM-D. All passives are integrated in the low cost MCM-D substrate. The sub-harmonic mixing is performed using a beam-lead anti-parallel diode pair mounted onto the MCM using thermocompression.

The BPSK modulator has a very flat conversion due to an optimal harmonic loading of the third harmonic of the LO: measurements show a +/- 0.25 dB variation on the conversion loss for an LO-frequency varying between 6.8-7.6 GHz. The LO and RF return loss are below -14 dB and -12.5 dB respectively. The I/Q vector modulator consists of a Wilkinson power divider, a CPW Lange coupler and 2 BPSK modulators. The QPSK-modulator has a measured image rejection better than -32 dB over the VSAT-operation band (RF: 14-14.5 GHz) corresponding to vector phase and amplitude errors lower than 1° and 0.1 dB. These results have been obtained without any on- or off-chip amplitude or phase tuning. The circuit also does not require any DC-bias.

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