Coplanar High Performance MMICs in MHEMT and PHEMT Technology for Applications up to 100 GHz

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In this paper we present coplanar MMICs based on both, metamorphic (MHEMT) and pseudomorphic (PHEMT) high electron mobility transistor technologies. Starting with a modulator-driver MMIC for optical transmission systems, we describe state of the art MMICs like a 94 GHz low-noise amplifier, a 35 GHz and a 60 GHz medium power amplifier and finally we demonstrate the feasibility of a monolithically integrated 94 GHz single-chip FMCW radar sensor.

INTRODUCTION

Coplanar MMICs have reached a high maturity in recent years making them excellent candidates for high performance millimeter wave systems. According to [1] several HEMT structures compete with each other, and the most suitable for the related application has to be chosen. As the increasing demand for bandwidth drives the operating frequency higher and higher, radar systems also benefit from this point, due to the improved spatial resolution and the compact size. Moreover, the FCC has recently liberalized the use of further frequency bands, i.e. the V-band around 60 GHz and the W-Band around 94 GHz. It can be expected that there will be a rising demand for circuits operating at these frequencies.

DEVICE CHARACTERISTICS

Most of the circuits demonstrated in this paper use a reliable, well proven AlGaAs/InGaAs/GaAs PHEMT technology with a gatelength of 0.15 µm. To extend the capability to realize ICs for even higher frequencies, a metamorphic HEMT process based on the InAlAs/InGaAs material system has been developed by [2]. Using this MHEMT technology on 4-inch GaAs wafers, devices with 100 nm gate length have been fabricated, as shown in Fig. 1. The transistors achieved a transit frequency of about 200 GHz, as illustrated in Fig. 2.

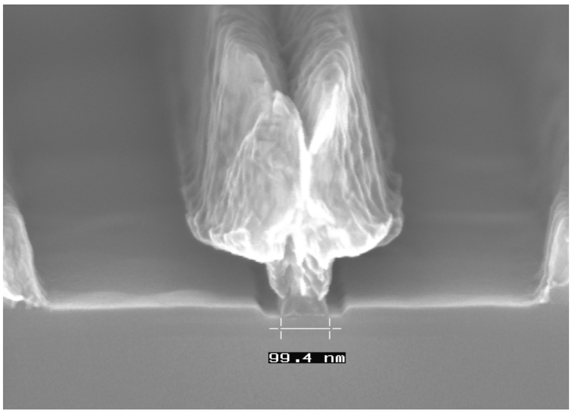

Fig. 1. SEM picture of 0.1µm MHEMT on GaAs substrate.

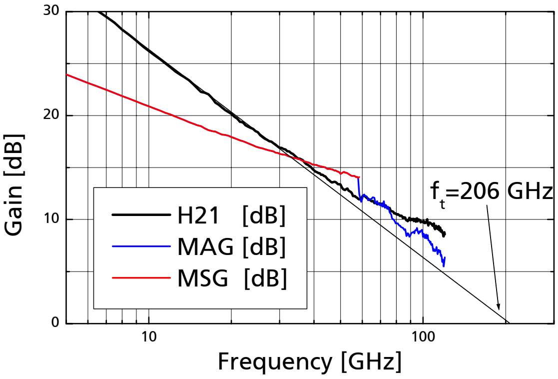

Fig. 2. Transit frequency for 0.1µm MHEMT (w_g=2x60 µm) based on measured S-parameters up to 120 GHz.

WIDEBAND DRIVER FOR OPTICAL COMMUNICATION SYSTEMS

Today 40 Gbit/s optical data transmit systems use optical modulators, because the direct modulation of the laser is not applicable due to the lack of modulation speed and added chirp. Therefore optical Mach-Zehnder modulators are frequently employed which in turn require high voltage swings in conjunction with large bandwidth. This problem is solved by the use of distributed amplifiers. Figure 3 shows an integrated TWA realized at the IAF, using 0.15µm PHEMT technology.

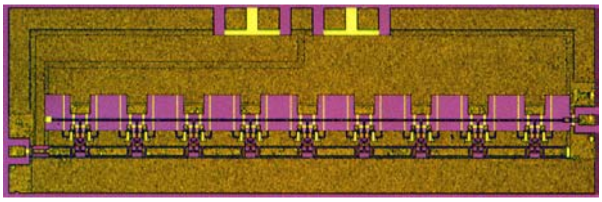

Fig. 3. Chip photograph of the nine section coplanar distributed amplifier.

To achieve the necessary output power a minimum over-all gate periphery is needed. If this gate periphery is distributed on only a few HEMTs, the artificial gate- and drain-lines of the distributed amplifier are loaded extensively by the capacitive elements of the active device, resulting in a reduced bandwidth. In the IC presented here nine sections with small devices (w_g = 2x20 µm) were used. According to [3], an overall bandwidth of 65 GHz and a gain of 12 dB was achieved by employing HEMTs in cascode configuration and applying the resonant peaking technique. The on-wafer measured small signal S-parameters of the modulators driver MMIC are shown in Fig. 4.

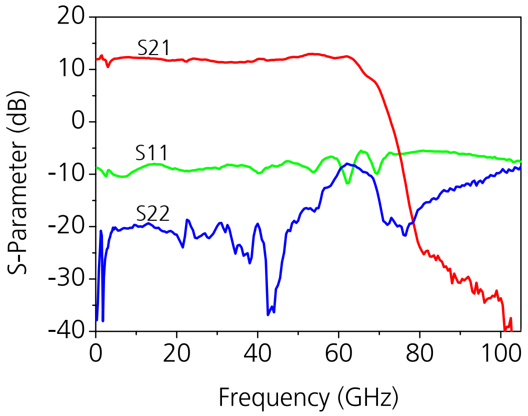

Fig. 4. On-wafer measured small signal S-parameters of the modulator driver MMIC.

Additionally fast rise- and fall-times for non-periodical signals and low group-delay variations are of importance to achieve widely open eye-diagrams. The measured eye-diagram of the TWA MMIC is shown in Fig. 5, demonstrating a voltage swing of 6 Vpp. The input signal for this measurement was a 40 Gbit/s PRBS signal.

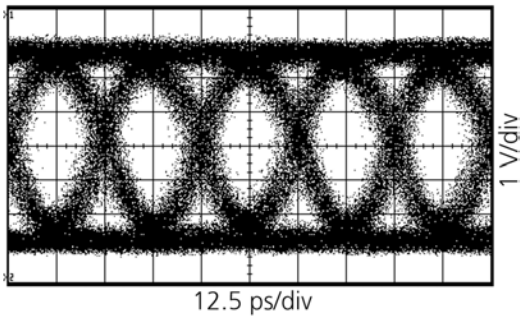

Fig. 5.Output eye-diagram of the 65 GHz distributed amplifier. The measured voltage swing is 6 Vpp.

94 GHZ TWO-STAGE LNA

For mm-wave imaging systems operating at 94 GHz, MHEMTs are perfectly suited because of their very low noise-figure. To show the capability of the IAF 0.1 µm MHEMT process a 2-stage LNA was designed using a 4x15 µm transistor as active device. Inductive lines were used in the source connection of the FETs. This reduces gain but it helps to bring the conjugate of Γ_{opt} closer to S_{11} to achieve simultaneous good noise- and input-matching. The amplifier has a small-signal gain of 8 dB and a noise-figure of 3.5 dB between 80 and 90 GHz as displayed in Fig. 6.

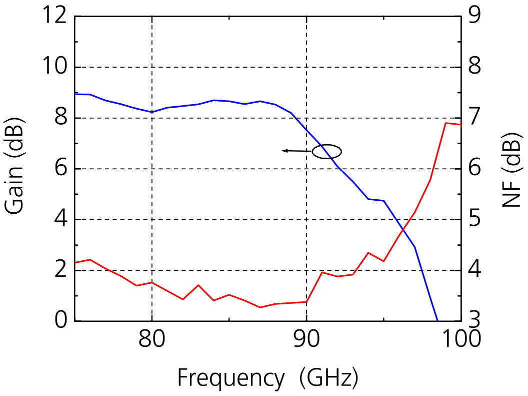

Fig. 6. Low-noise amplifier with 8 dB gain and 3.5 dB noise figure in the frequency range from 80 - 90 GHz.

The chip-size of the LNA is only 1x2 mm². A photo of the coplanar MMIC is depicted in Fig. 7. The size of the circuit still can be reduced by 20 % if the 50 Ω line at the output is removed, which was added here due to mask design.

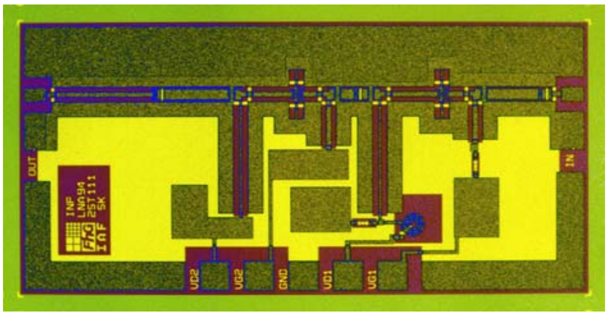

Fig. 7. Chip-photo of the 2-stage94 GHz low-noise amplifier.

COPLANAR POWER AMPLIFIERS

Coplanar technology is used in small signal designs but also offers good performance in watt-level power amplifiers. As an example a 35 GHz two-stage design on a 0.15µm PHEMT process is chosen [4]. The chip as displayed in Fig. 8 was designed for flip-chip mounting on an appropriate carrier substrate. The galvanically grown gold bumps have two functions: first, to provide the signal and bias connection to the active devices, and second, to act as a thermal drain for the dissipated power of the transistors. These thermal bumps are placed on the source islands of the 8x60 µm wide FETs.

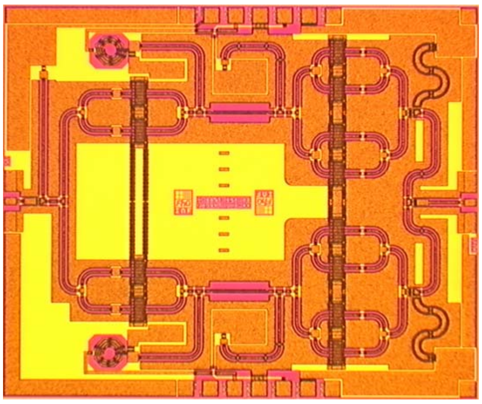

Fig. 8. Layout of the two-stage 35 GHz power amplifier. Chip-size is 2.45x2.95 mm^2.

The measured output power of the design is 29.8 dBm at the P_{1dB} compression point and 30.8 dBm in saturation at a channel temperature of 60 °C. The obtained small signal gain was 10 dB. Fig. 9 shows the on-wafer power measurement carried out on a thermal chuck for two different channel temperatures of 60°C and 85°C. A decrease of 0.8 dB of the P_{-1dB} compression point and 0.5 dB for the saturation power is visible at 85 °C junction-temperature (T_j) compared to 65 °C T_j.

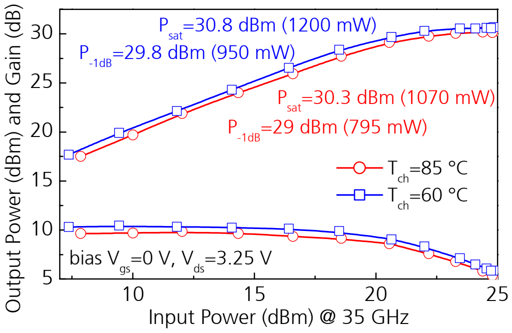

Fig. 9. On-Wafer power measurement using a thermal chuck at channel temperatures of 60 °C and 85 °C.

As short range communication at 60 GHz is becoming more popular, there is a rising need for medium power amplifiers with compact chip-dimensions. The discussed design was realized on our 0.15µm PHEMT technology. To achieve reasonable gain together with a small circuit size, the amplifier utilizes two dual-gate stages. The output stage is made of two paralleled 4x75 µm dual-gate FETs to achieve sufficient output power. On-wafer measurements showed an output-power of 19 dBm at the 1 dB-compression point and 21 dBm in saturation. The small signal gain is 14 dB and the in- and output return losses are better than –10 dB at 60 GHz. The current consumption was 325 mA at a drain voltage of 4 V. The gain and output power versus input power at 60 GHz is shown in Fig. 10.

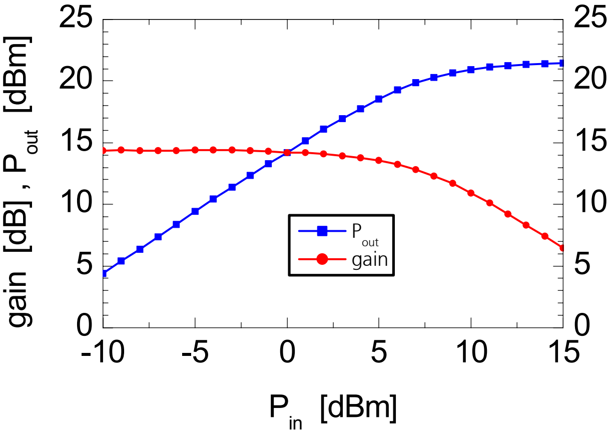

Fig.10. Gain and output power compression characteristic of the 60 GHz MPA.

SINGLE CHIP 94 GHZ FMCW RADAR SENSOR

To demonstrate the versatility of coplanar MMICs we present a single chip 94 GHz FMCW radar sensor for industrial high resolution sensor applications [5]. The complete system consists of a VCO with injection port, an

MPA, a transmit-receive coupler, an LNA and finally a resistive down-converter mixer as depicted in Fig. 11.

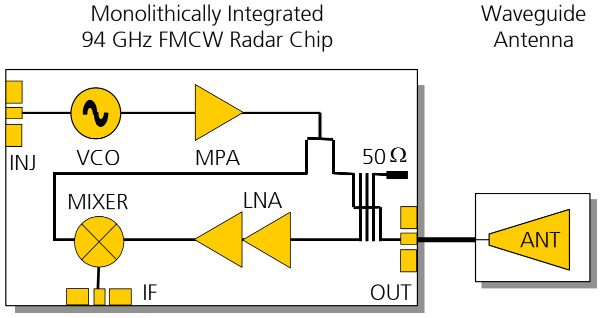

Fig. 11. Block diagram of the FMCW radar chip.

The VCO can be tuned in a range of 6 GHz from 91 GHz to 97 GHz. The option of injection-locking can be used to improve the phase noise behavior. The MPA and the LNA use very compact cascode HEMTs in order to save chip-area. The VCO signal is amplified and afterwards split up once for the transmit path and to serve as the LO input signal for the mixer. In the transmit path a directional Lange-coupler takes the place of a circulator used in an earlier version, resulting in the advantage of a monolithic integration and a drastically increased bandwidth. The received signal, coming from the antenna, is coupled into the two-stage LNA and finally fed into a resistive down-conversion-mixer. The complete chip mounted in a W-band waveguide module is depicted in Fig. 12.

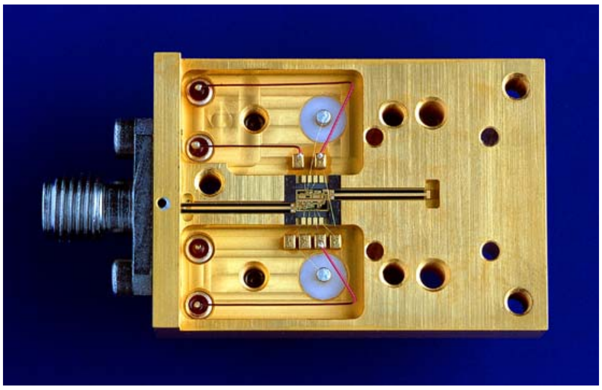

Fig. 12. Photo of the single chip 94 GHz FMCW radar sensor mounted into a waveguide module. The chip-size is 2x3 mm².

CONCLUSION

Coplanar MMICs based on PHEMT and MHEMT technologies have the ability to fulfill the strong requirements of tomorrows communication and sensor systems. The approach to successfully integrate several functions at 94 GHz into a single FMCW-radar chip shows the maturity of both the process technology and the models. Table (1) summarizes the characteristic data of the MMICs presented in this paper.

Circuit	Frequency Range /GHz	Distinctive feature	Chip-size
Modulator-Driver	dc-65 GHz	output voltage swing 6 Vpp	2.3 mm²
MHEMT LNA	80 –90 GHz	NF=3.5 dB	2 mm²
Cascode MPA	60 GHz	21 dBm Psat	2 mm²
Power Amplifier	35 GHz	29.8 dBm @ P_{1dB}	7.3 mm²
FMCW radar chip	94 GHz	fully integrated	6 mm²

Table 1. Summary of MMIC features.

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