MMIC Balanced Vector Modulators for Millimetre-Wave Digital Communications Applications

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ABSTRACT

There is considerable demand for low cost, high performance, millimetre-wave transmitters for digital communications applications. Direct carrier modulation is an ideal solution to this challenge since it minimises the complexity of the mm-wave subsystems. In this paper the design and performance of balanced MMIC vector modulators operating at 38 GHz are described. It is shown that the balanced bi-phase amplitude modulator elements yield accurate constellations with broadband operation from 20 to 40 GHz. 16-QAM modulation can be produced directly at 38 GHz using this technique, with no fine tuning required. With careful calibration of the vector modulator very high precision can be achieved, and 256-QAM signals have been generated to demonstrate this capability.

1. INTRODUCTION

Direct modulation of the carrier signal [1,2] has been shown to be an attractive means of reducing hardware complexity and cost for wireless applications. If a conventional microwave mixer is used to up-convert the modulated signal, from a low frequency to the transmission frequency, it would be impractical to filter out the unwanted sidebands at the carrier frequency. As a result, a transmitter usually requires an IF modulator followed by a complex chain of mixers, filters and amplifiers. However, for millimetre-wave applications where cost remains a major factor restricting the widespread use of wireless systems, direct modulation is a very attractive means of realising low cost transmitters. Simple modulators for schemes such as amplitude-shift keying (ASK), binary phase-shift keying (BPSK) and frequency-shift keying (FSK) can be designed using a wide range of techniques. For quadrature modulation schemes, such as quaternary (or quadrature) phase-shift keying (QPSK) and quadrature amplitude modulation (QAM), an I-Q vector modulator is widely used [3-8]. In this technique a quadrature 3dB power divider is used to create the two orthogonal channels and an individual bi-phase amplitude modulator is assigned to each channel. The output signals from these amplitude modulators are then combined using an in-phase 3dB power combiner (e.g. a Wilkinson combiner). Most often, double-balanced mixers are used as the bi-phase amplitude modulators, but these are quite large and difficult to design. Alternative techniques are not simple to realise with high performance at mm-wave frequencies, however, because the device parasitics cause large amplitude and phase errors. It is very difficult to tune out these parasitics in a wideband design.

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2. BALANCED BI-PHASE AMPLITUDE MODULATORS

A W-band balanced BPSK modulator employing switched amplifiers was reported by Lo, et al., [9]. Here, a pair of amplifiers is configured in a topology similar to a balanced amplifier, employing input and output Lange couplers. However, the output is taken from the isolation port, which is normally terminated with a 'dummy' load. As a result, if the amplifiers are switched ON and OFF in a push-pull mode then a BPSK signal is generated at this isolation port. In an expanded paper Lo, et al., introduced an alternative solution employing reflection-type switching elements instead of switched amplifiers [10]. The natural cancellation properties of this balanced modulator ensure broadband operation with near perfect BPSK performance, even at millimetre-wave frequencies.

For multi-level QAM, an I-Q vector modulator is realised employing two balanced bi-phase modulators operated in quadrature. Each bi-phase modulator has to be operated at a number of different amplitude settings (e.g. 2 settings for 16-QAM and 8 settings for 256-QAM, each with 0° and 180° phase offset) and still needs to be operated in a push-pull mode. In the technique presented here, the FETs are used as variable-resistance elements controlled by an analogue signal at its gate terminal. Analogue vector modulators have recently been shown to have advantages for signal processing in communications applications [11]. For example, analogue control allows excellent sidelobe suppression to be achieved in digital communications and can be used for performing small-shift frequency translation [12]. However, when sweeping the full resistance range there is no guarantee that the constellation is perfect: whilst the balance of the circuit is perfect for any pair of diametrically-opposite points on the constellation, it is not always the case that all the different pairs of constellation points line up together properly. So it is necessary to investigate this behaviour in detail by characterising the variable resistance elements and then investigating the practical performance of the bi-phase amplitude modulator.

3. CHARACTERISATION OF THE VARIABLE RESISTANCE TERMINATION

The circuit topology of the standard reflection-type bi-phase amplitude modulator used here is illustrated in Fig. 1. Variable resistance terminations are realised using a voltage-controlled cold-FET. Here, the drain termination of a standard FET is unbiased and a variable voltage is applied across the gate-source terminations. With a depletion-mode FET, the depletion region expands when the negative bias voltage increases. As a result, the drain-source channel resistance increases. When the bias voltage is equal to the pinch off voltage, the channel resistance will be very large. Ideally, the cold-FET has zero drain-source resistance at zero bias and infinite resistance at the pinch-off voltage. In practice, however, the channel resistance at zero bias is much larger than zero (due to contact and access resistances), and although a very large resistance is obtained at pinch-off, the overall impedance is dominated by the reactance of the inherent shunt capacitance.

GEC-Marconi’s commercial H40 pseudomorphic HEMT process was used for this study. Here, 0.25μm gate length AlGaAs/InGaAs pHEMTs are fabricated on 3 inch diameter and 100μm thickness wafers. Accurate modelling of cold-pHEMTs was performed using 1-port S-parameter measurements of a specially laid-out 2x60μm cold-pHEMT. The Smith chart plot of $S_{11}$ against bias is illustrated in Fig. 2. It can be seen that the performance is far from ideal, suffering from huge amplitude and phase errors.
4. BALANCED BI-PHASE AMPLITUDE MODULATOR

The circuit diagram of the balanced bi-phase amplitude modulator is shown in Fig. 3. Using an equivalent circuit of the GMMT cold PHEMT the expected attenuation and phase responses of the balanced modulator have been calculated. A comparison between the expected responses of the standard and the balanced modulator are illustrated in Fig. 4(a) and 4(b). It can be seen that excellent performances can be achieved when using the balanced modulator. Firstly, with reference to (a), it is found that 256-QAM is possible. However, this is not the case with the simple modulator, as all the necessary amplitude settings can not be covered and the phase error is very large.

The measured response of the actual chip, measured using a Cascade on-wafer probe station and HP8510C vector network analyser, is plotted in Fig. 5. Comparing this with Fig. 2, one can see that the balancing technique dramatically improves the amplitude and phase accuracy. Furthermore, the circuit achieved good matching with minimal amplitude and phase error over the entire 20 to 40 GHz frequency range. Operating as a BPSK modulator, the chip was tested using a 2 Mbit/s pseudo-random sequence generator and an HP8562 spectrum analyser. The corresponding measured output spectral response is given in Fig. 6, showing a near perfect BPSK profile.

5. BALANCED VECTOR MODULATOR

A microphotograph of the complete monolithic 38 GHz balanced vector modulator, which measures only 1.6 x 2.0 mm$^2$, is shown in Fig. 7. A National Instruments AT-AO-6 data-acquisition board was programmed to generate the 2 sets of complimentary pseudo-random sequence baseband signals: $I$ & $I^*$ and $Q$ & $Q^*$. The raw constellation measurements of the vector modulator, having no correction, can be seen in Fig. 8 for 16-QAM. For higher levels of modulation, the slight imperfections in the performance become more noticeable. For example, phase imbalance from ideal quadrature means that the constellation is not perfectly square. Fortunately, with analogue control it is possible to correct these errors by careful adjustment of the $I$ and $Q$ signals. $I$ and $Q$ become interrelated, because if a constellation point is (for example) slightly south-west of its intended position both its horizontal and vertical positions must be fine tuned. Therefore, a calibration procedure must be performed in which the $I$ and $Q$ voltages for each constellation point are found. These voltages are stored in a look-up table and a digital-to-analogue converter (DAC) can then be used to generate the voltages in real-time. A near-perfect 256-QAM constellation has been achieved at 38 GHz after a quick manual calibration was performed. The magnitude and phase performance is within ±1% and ±2%, respectively. Higher accuracy and levels of modulation greater than 256-QAM (e.g. 1024-QAM) could be achieved with an automated calibration procedure. The ultimate limits being practical issues such as limited DAC precision and changes in circuit performance with temperature. In principle, both these limitations could be addressed with suitable engineering.

6. CONCLUSIONS

The balanced modulator using reflection-type attenuators is an extremely robust technique which gives near perfect BPSK performance with negligible design effort. By employing two such modulators in an I-Q modulator, near perfect QPSK performance can be achieved. As a modulator for multi-level digital modulation the circuit exhibits some degradation in performance with practical variable resistance elements, but with fine-tuning excellent
constellations can be achieved. Using a simple look-up table technique, to calibrate the vector modulator, it has been shown that multilevel direct carrier modulation can be implemented at 38 GHz with negligible hardware complexity. The simplicity of the circuit topology leads to a compact chip with high yield, because the FETs are used only as variable resistance reflection terminations. In conclusion, balanced vector modulators have been shown to be very promising for implementing high performance millimetre-wave transmitters for digital communications applications.

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REFERENCES

Fig. 1. Circuit topology of the bi-phase amplitude modulator

Fig. 2. 2x60μm Cold pHEMT S11 vs. bias voltage, at 60 GHz

Fig. 3. Balanced bi-phase amplitude modulator circuit

Fig. 4. (a), (b): Simulated attenuation and phase shift as a function of one varying bias for the balanced modulator compared with the standard modulator.
Fig. 5. Measured S21 vs. bias for the 38 GHz BPSK balanced modulator.

Fig. 6. Measured spectral response of the 2 Mbits/s data rate BPSK signal at 38 GHz.

Fig. 7. Microphotograph of the complete 38 GHz balanced vector modulator.

Fig. 8. Raw 16-QAM performance of the vector modulator at 38 GHz.