MMIC Circuits Enable Direct-Carrier Modulation

The combination of a single-chip transmitter and an amplitude-control chip is proposed to implement multilevel amplitude modulation.

S. Nam, A.E. Ashktani, and I.D. Robertson
Microwave Circuits and Devices
Research Group, Kings College, Dept.
of Electronic & Electrical
Engineering, The Strand, London
WC2R 2LS, United Kingdom.
S. Lucyzen
Millimetre-wave Research Team,
University of Surrey, Guildford,
Surrey, United Kingdom.

CONVENTIONAL microwave transmitter designs are based on modulation at the intermediate frequency (IF), requiring a complex chain of mixers, filters, and amplifiers to upconvert the modulated signal to the transmission frequency. By applying direct modulation of the microwave carrier signal, a significant reduction in system hardware requirements is achieved. A single-chip transmitter design for indoor radio communications provides direct-carrier modulation in the 17/18-GHz frequency range, employing a microwave-monolithic-integrated-circuit (MMIC) phase shifter and variable attenuator to provide phase and amplitude control. This second part of a two-part article presents the physical realization of the phase- and amplitude-control circuits—which are implemented with a voltage-controlled oscillator (VCO) and 360-deg. phase shifter on one chip and an amplitude modulator on a separate chip. The structure and performance of the balanced vector modulator (which is realized by cascading two amplitude biphase modulators) will also be described.

The first part of the article evaluated the circuit topologies available for implementing the phase shifter and variable attenuator. The basic structures of the in-phase/quadrature (I/Q) and phase-shifter/variable-attenuator types of vector modulators were overviewed, and it was noted that the latter type can be implemented in a much smaller chip area. In fact, digital-signal-processor (DSP) technology may be employed to convert the I and Q baseband signals into equivalent amplitudeand phase-controlled voltages—resulting in reduced cost as well as simpler adaptation to the various air interfaces and transmission protocols that are used worldwide.

Analog-control circuits were chosen for the transmitter chip due to their simpler topology (only a single central voltage is needed and zero DC power is consumed). An interdigitated phaser Schottky-varactor-diode (IPSVD) structure was selected to implement the phase shifter, while a voltage-controlled cold metal-semiconductor field-effect transistor (MESFET) was chosen to obtain the tunable resistance needed for the variable attenuator. Circuit synthesis using the reflection-type topology (which is employed for the phase shifter and variable attenuator) was also reviewed.

FABRICATED CHIPS
The fabricated MMICs consist of a VCO and 360-deg. phase shifter on one chip, with a separate amplitude-modulator chip. This configuration is required since most indoor radio applications currently specify modulation schemes such as quadratura...
ture phase-shift keying (QPSK) or Gaussian minimum-shift keying (GMSK), which can be realized directly by the VCO and 900-deg phase shifter as a single-chip transmitter. However, the option of separate amplitude control is desirable in order to provide correction of the phase shifter’s amplitude variations and to facilitate the realization of re-tuning. Amplitude modulation (AM-ASK) for future applications. Figure 10 presents the MMIC transmitter chip, which measures 2 × 3 mm. The carrier frequency is controlled by using the tuning voltage of the VCO and can be phase-locked externally. The VCO uses a negative-resistance series-feedback topology and is designed for a center frequency of 17.2 GHz, with a tuning range of approximately ± 1 GHz.

VCO Design

Figure 11 shows a circuit diagram of the VCO. The circuit includes a series-feedback varactor diode (capacitance C1) in the source, a resonator (formed with inductance L1 and varactor diode VD1) on the gate terminals, and a matching network (which includes inductors L5 and L6-9) that incorporates the drain D2 biasing. The feedback capacity on the source is required in order for the FET to present a negative resistance to the DC source.

The design of the VCO was optimized primarily through small-signal analysis in order to optimize the oscillation conditions for a large gain peak of the VCO at resonance as well as a negative input resistance with a resistance of zero. In order to increase the tuning range of the oscillator, a 6 × 150 μm varactor diode was used. Feedback capacitor C2 controls the negative-feedback resistance value.

The M-array PSK modulator uses a four-stage reflection-type phase shifter with varactor diodes. This 90°-degree phase shifter consists of four cascaded 90°-deg phase-shifter sections. Figures 12a and 12b show the schematic of the 90°- and 360°-deg, phase-shifter respectively. Varactor diodes connected back-to-back are used for improved RF power handling. The diodes are biased through 3-kW resistors, which are employed to provide high isolation as well as forward-biasing current limiting. These high-value resistors are non-critical for most control applications, but may cause a significant reduction in the maximum data rate when the circuit is applied to digital modulation schemes. Figure 13 demonstrates the measured response of the transmitter chip at 18 GHz. These results show that PSK modulation can be achieved with full 360-degree coverage. Only small amplitude variations are exhibited.

Through appropriate control of the phase-control bias lines, the PSK-modulated spectrum was obtained (Fig. 14). Since PSK employs two bits per symbol, the bias lines are configured so that each of the bits is in every symbol applied to one pair of 90°-deg, phase-shifter sections. In terms of IQ systems, one pair of 90°-deg sections is driven by the I channel while the other pair is driven with the Q channel.

AMPLITUDE CONTROL

Figure 15 shows the MMIC amplitude-control chip, which measures 0.6 × 1 mm. The design uses 6 × 106 μm wide FETs for tunable resistance, output power, and feedback terminations. Even though several papers have reported on analog reflection-type attenuators that employ a resistive and FET reflection termination, the insertion phase change over the attenuator’s amplitude-controllable range—which represents a critical performance parameter—unfortunately, since the cell FET has significant parasitics, it was found that at the amplitude-control circuit’s high operating frequencies, the insertion phase change can vary quite dramatically over the full attenuation range. One way to minimize the phase-shifter variation is to turn off the parasitic resonant elements. However, this approach is not sufa-
ABLE FOR WIDE OPERATING BANDWIDTHS AND IS DIFFICULT TO IMPLEMENT OVER THE FULL ATTENUATION RANGE.

The solution used in the direct-coupler-modulation design described here is to cascade two attenuator chips in an arrangement where the unwanted phase shifts cancel out. Figure 16 demonstrates the measured attenuation at various bias settings over the 10- to 30-GHz frequency range. It can be seen that wideband operation is attained. The phase variation over the full range is ±20°, which can be accommodated by properly adjusting the phase shifter. It should be noted that 16QAM, for example, only requires an amplitude variation of less than 10 dB. Consequently, the phase variation is small for this application.

VECTOR MODULATOR

A monolithic millimeter-wave vector modulator has been realized for use in multilevel direct-coupler-modulation transmitters. It is shown that by employing balanced biphase amplitude-modulator elements, accurate constellations are achieved, along with broad-band operation from 20 to 40 GHz. It is found that this technique is very robust, and the resulting analog vector modulator represents a key component for many millimeter-wave communication applications.

Each balanced biphase amplitude modulator uses a pair of reflection-type attenuators that are operated in a push-pull configuration. The input signal is effectively split using a balun, and the outputs from each branch (which are driven with complementary control voltages) are combined in-phase. The combined output is obtained as the vector sum of the two transmission coefficients. Since one branch is ON and the other is OFF, the response is perfectly symmetrical if the balun is ideal.

Since baluns are difficult to implement in MMICs, it is easier to use two Lange couplers in order to realize the 180°-deg. operation. One Lange coupler is placed at the input and the other is placed at the output of an ar-

rangement similar to that of a balanced amplifier (Fig. 17).

However, the cold FETs used to implement the variable-resistance control are not suitable for broadband amplifier operation. As a result, the output is directly opposite the input (and not diagonally opposite the input, as in a balanced amplifier). Lange couplers provide a nearly ideal phase response, and the balanced binary-phase-shift-keying (BPSK) modulator delivers near-perfect amplitude and phase balance.

For multilevel modulation schemes, the cold pseu-
domorphic high-electron-mo-

bility transistors (PHEMTs) are controlled with an analog gate-bias signal to yield a variable magnitude for the reflection coefficient. This way, the circuit provides a continuous range of positive and negative transmission values and can be used as the basis of a standard 16QAM balanced vector modulator (as demonstrated in Fig. 17).

The vector modulator can be employed to implement multilevel digital-modulation schemes such as QPSK and 16QAM.

The MMIC balanced vector modulator measures only 1.6 x 2.0 mm. Figure 18 presents the raw performance of the vector modulator at 38 GHz, showing the 16QAM constellation measured with no correction.

As a vector modulator for multilevel digital-modulation systems, the circuit exhibits some degradation in performance with practical variable-resistance elements. With some fine-tuning, however, excellent constellations are easily achieved. The simplicity of the circuit topology leads to a compact chip with high yield, since the devices are used only as variable-resistance reflection-tolerant terminations. Overall, the vector-modulator design is an excellent tech-

MICROWAVES & RF • MAY 1998
**RF, Microwave & Digital Specialists**

- Ground, S/A, Antenna Sub-systems & Components
- Weather Radar Sub-systems
- Terrestrial & Satellite Microwave Systems
- Satellite Transmission & Transponder Monitoring Systems

---

**CONCLUSIONS**

At low frequencies, fully active double-balanced mixers are small in size—making the MMIC IQ vector modulator a viable design. At higher frequencies, however, double-balanced mixers requiring transmission lines become larger and consume a considerable chip area. The amplitude/phase vector modulator is proposed as a lower-cost alternative at these operating frequencies. Analog amplitude and phase-control circuits have been studied since they offer simplicity, do not require any DC power, and can potentially provide low sideband levels.

The chosen topologies have been implemented using the F20 GaAs MESFET process from GEC-Marconi Materials Technology (GMMT, Towcester, United Kingdom). The single-chip transmitter operates at high bit rates while providing amplification flexibility, size is useful for BPSK, QPSK, and GMSK modulation schemes. In addition, amplitude modulation can be obtained in principle by adding the variable attenuator chip at the output. With this approach, the two RF signals are added on-chip.

---

**SERIES}

**INTELEX**

A company of the Easton Group

Park Road, Burnage
Isle of Wight, PO33 2BU, UK

Tel: +44 1983 817300
Fax: +44 1983 854705

Website: http://www.pascal.co.uk

E-mail: sales@pascal.co.uk

US Sales Office
Tel: 1-800-644-8689 x455
Tel: +1-801-424-8044
Fax: +1-801-424-4167

---

**DESIGN FEATURE**

**Direct-Current Modulation**

---

16. The measured attenuation (a) and phase (b) of the cascaded attenuator were obtained at various bias settings.
17. The biphase balanced amplitude modulator forms the foundation for a standard IQ balanced vector modulator. Circuits can in principle provide multilevel amplitude modulation. In practice, however, the phase error in the attenuator and the amplitude error in the phase shifters are too high to enable this setup to provide accurate signal constellations.

To combat this problem, look-up tables can be used—with the errors from one chip corrected by adjusting the other chip. In theory, this solution can lead to an ideal modulator with many applications. This research area is expected to be very fruitful, with many more aspects requiring additional study in order to facilitate the com-

16. The 10GHz constellation for the MMIC vector modulator (without correction) was obtained at 38 GHz.
meral application of this type of modulator in the future. **

Acknowledgment

The authors wish to thank Mr. G. Agnew and Mr. J. A. Agnew for useful discussions regarding the design of the modulator. The authors also wish to thank Mr. B. J. Stainer and Mr. R. J. Smith for their assistance in the measurement of the performance of the modulator. The authors would also like to thank Dr. D. J. A. Maclean for his valuable comments on the manuscript.

References