60-GHz Integrated-Circuit High Data Rate Quadriphase Shift Keying Exciter and Modulator

ALBERT GROTE AND KAI CHANG, MEMBER, IEEE

Abstract—**An integrated-circuit quadriphase shift keying (QPSK) exciter and modulator have demonstrated excellent performance directly modulating a carrier frequency of 60 GHz with an output phase error of less than 3 degrees and maximum amplitude error of 0.5 dB. The circuit consists of a 60-GHz Gunn VCO phase-locked to a low-frequency reference source, a 4th subharmonic mixer, and a QPSK modulator packaged into a small volume of 1.8×2.5×0.35 in. The use of microstrip has the advantages of small size, light-weight, and low-cost fabrication. The unit has the potential for multigigabit data rate applications.**

I. Introduction

FUTURE COMMUNICATION systems will require direct modulation at 60 GHz to enhance the signal processing capability. For most systems, particularly space applications, small and lightweight components are essential to alleviate severe system design constraints. Thus, to achieve wide-band, high data rate, and small size, direct modulation techniques at millimeter waves using solid-state integrated-circuit technology are an important part of technology development.

Integrated-circuit and waveguide phase shift keying modulators have been fabricated for use in digital communications at microwave frequencies [1]–[4]. Because of dimension limitations, innovative design modifications have to be devised to apply these techniques at 60 GHz.

This paper presents an integrated-circuit quadriphase shift keying (QPSK) exciter/modulator directly modulating a 60-GHz carrier frequency with state-of-the-art performance. An output phase error of ±3 degrees and amplitude error of ±0.5 dB have been achieved. The modulator was designed for multigigabit data rates.

II. System Description

Fig. 1 is a functional block diagram of the exciter/modulator. The system consists of three major parts: a 60-GHz stable source as the exciter, a QPSK modulator, and a data driver. The 60-GHz source contains a microstrip Gunn VCO phaselocked to a low-frequency reference source to achieve high stability and low FM noise. The output power is coupled into the QPSK modulator with modulated outputs controlled by the data driver. The modulated quadriphase output is fed to a waveguide through a microstrip-to-waveguide transition.

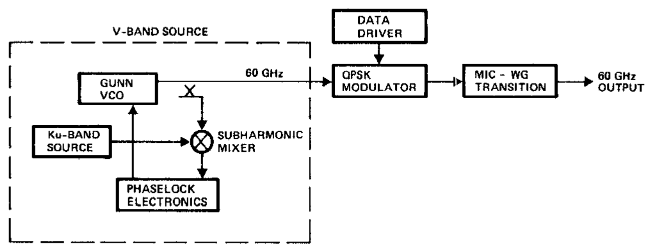

Fig. 1. Block diagram of QPSK exciter/modulator.

III. 60-GHz Exciter

The 60-GHz exciter consists of a Gunn VCO phase-locked to a low-frequency reference source to achieve high stability and low FM noise. The Gunn VCO is phaselocked to a stable 14.4828-GHz reference signal through a 4th subharmonic mixer to generate a 2.06896-GHz IF signal. The 14.4828-GHz reference signal is generated from the 2.06896-GHz stable source through a ×7 frequency multiplier. The IF signal from the subharmonic mixer is then fed into the phase detector where it compares with the 2.06896-GHz output from the stable source and controls the Gunn VCO.

The microstrip Gunn VCO and 4th subharmonic mixer have similar designs as previously reported [5]. The Gunn VCO was built on 5-mil Duroid substrate in microstrip. Fig. 2 shows the circuit layout. A two-section microstrip transformer was designed to match the Gunn impedance to the 50-Ω line impedance. A varactor chip was mounted next to the Gunn diode to achieve electronic tuning. The performance of this Gunn VCO is shown in Fig. 3. A varactor tuning range of over 500 MHz has been achieved with greater than +11-dBm output power at 60 GHz. The tuning is quite linear and the output power is reasonably flat over the tuning range, which is sufficient for phaselock applications.

The 4th subharmonic mixer is required to mix the 60-GHz RF output from the Gunn VCO with a 14.4828-GHz reference signal to generate a 2.06896-GHz IF signal. The IF signal is then fed into the phase detector which, in turn, controls the Gunn VCO. With minimum circuit optimiza-

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The authors are with the TRW Electronic Systems Group, One Space Park, Redondo Beach, CA 90278.

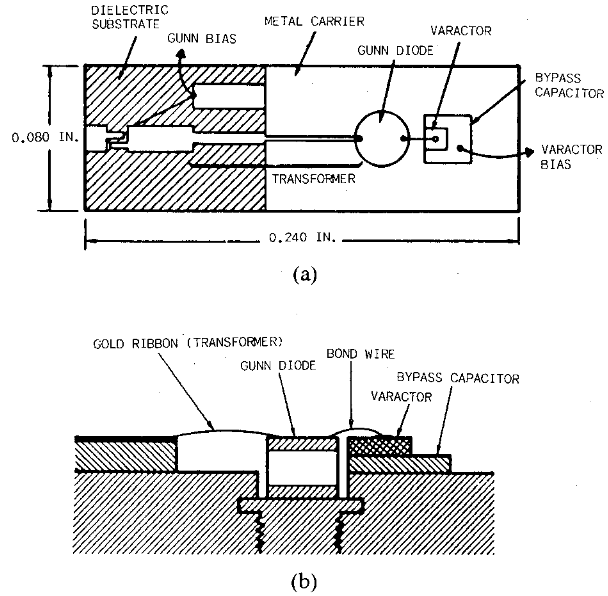


Fig. 2. Gunn VCO circuit layout.

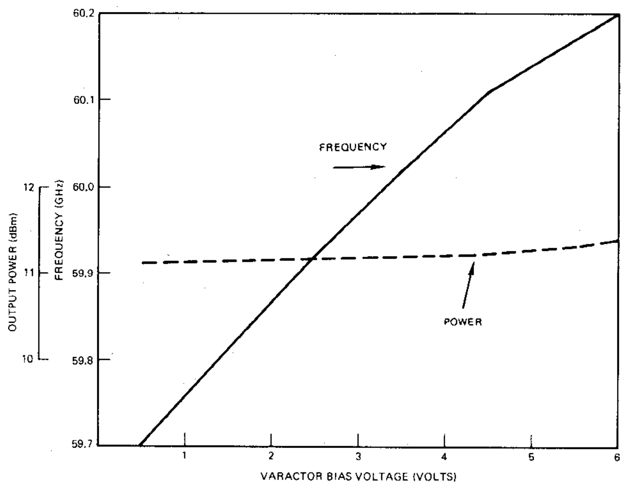


Fig. 3. 60-GHz Gunn VCO performance.

tion, a conversion loss of 15 to 20 dB at 60 GHz was achieved.

Fig. 4 shows the spectrum of a free-running Gunn oscillator and the phaselocked output spectrum. It can be seen that a very clean signal has resulted from the phaselock. The inner noise pedestal is due to the multiplied phase noise and loop bandwidth of the *S*-band source.

IV. QPSK Modulator

A block diagram and circuit layout of the QPSK modulator are shown in Fig. 5. The circuit consists of a Wilkinson power splitter with a 90-degree phase shift introduced in one leg, two biphase switches, an in-phase power combiner, and a microstrip-to-waveguide transition at the output. This configuration offers a simple and direct approach to generating a QPSK modulated signal.

The circuit operates as follows. The unmodulated RF carrier enters the circuit on microstrip and goes to the in-phase power divider. The signal is divided into two

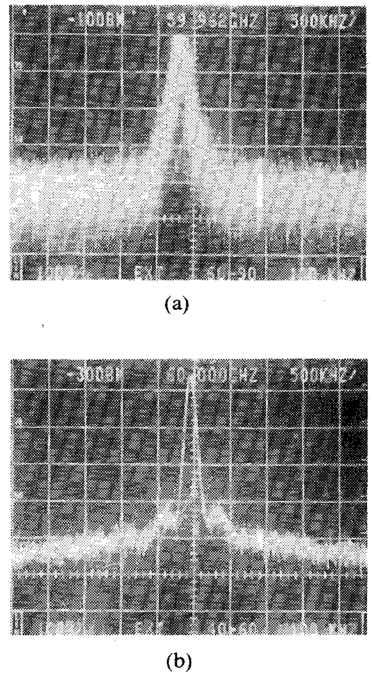


Fig. 4. Spectra of (a) a free-running Gunn oscillator, horizontal scale: 500 KHz/div and (b) a phaselocked Gunn oscillator, horizontal scale: 500 KHz/div.

equal amplitude in-phase signals. One arm of the power divider drives the biphase switch No. 1 directly. A 90-degree phase shifter is introduced at the input of biphase switch No. 2. This is achieved by increasing the microstrip path length between the power divider and biphase switch No. 2.

The biphase switches introduce an additional 0 or 180-degree phase shift to each signal as the data inputs switch the Schottky diodes. The two biphase-modulated signals are then summed in an in-phase power combiner producing a quadriphase modulated signal.

The modulator used has the following design features and advantages:

- high isolation between the carrier input port and the modulated carrier output port is obtained due to the balanced configuration;
- instead of using a 90-degree hybrid, the 90-degree phase shift is introduced by path length (this simplifies the design since a low-loss, well-balanced 90-degree hybrid is difficult to realize at 60 GHz);
- a dc return path is not required because slotlines are used;
- the 180-degree phase shift is introduced by the built-in field distribution of the slotline;
- a simple configuration using only a wire bonding is sufficient for baseband input circuit;
- small size is achieved by using a sapphire substrate.

A. Power Divider/Combiner

Two designs were considered for the 90-degree power divider: a 90-degree branchline coupler and an in-phase divider with a 90-degree length of transmission line in one

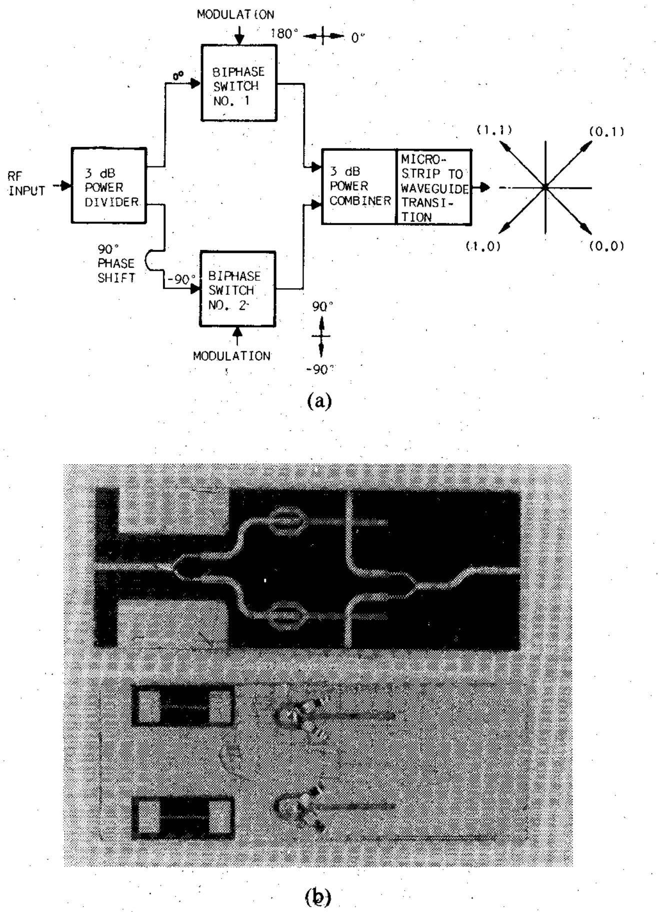


Fig. 5. Block diagram and circuit layout of a QPSK modulator chip (shown are both sides of the chip).

leg. The 90-degree branchline is a more complicated structure and requires compensations at the junctions that are difficult to fabricate at 60 GHz. For example, a 35-Ω line is required in the branchline coupler. With a 5-mil-thick sapphire substrate, a line width of 9 mils is required. This line has a quarter wavelength of 18 mils at 60 GHz. Thus, a quarter wavelength is only twice as long as its width and junction effects dominate the circuit response. The in-phase divider was chosen based on its less complicated structure.

The three-port Wilkinson-type hybrid was selected for its simplicity and good performance [6]. The circuit was first built and optimized at 15 GHz and then scaled up to 60 GHz. Typical performance is an insertion loss of 1 to 1.5 dB and isolation of 20 dB.

B. Biphase Switch

The biphase switch is the key component in the QPSK modulator. The circuit consists of two microstrip-to-slotline transitions, two beamlead Schottky-barrier diodes, two quarter-wavelength slotline paths, and a microstrip low-pass filter.

The switch uses a shunt-mounted configuration. The shunt-mounted structure is preferred for its higher isolation compared with the series-mounted configuration. The low isolation of a series-mounted structure is believed to be due to the high package capacitance associated with beamlead Schottky-barrier diodes. Considering the diode junction capacitance C_j, series resistance R_s, and, neglecting the package parasitics, the insertion loss is given by

$$\alpha_L = 20\log(1 + R_s/Z_0)\,\text{dB} \tag{1}$$

and the isolation is obtained by

$$\alpha_I = 10\log\left[1 + \left(\frac{1}{4\pi f C_j Z_0}\right)^2\right]\text{dB}. \tag{2}$$

Z_0 is the transmission-line impedance. Therefore, the lower the value of R_s and the lower the value of C_j, the lower the insertion loss and higher the isolation.

The Schottky-barrier diodes have typical series resistance of 5 Ω and junction capacitance of 0.05 pF. The calculated insertion loss at 60 GHz is about 0.8 dB, and the isolation is 1 dB.

For a shunt-mounted structure, the insertion loss is calculated by

$$\alpha_L = 10\log\left[1 + (\pi f C_j Z_0)^2\right]\text{dB} \tag{3}$$

and the isolation is given by

$$\alpha_I = 20\log(Z_0/2R_s + 1)\,\text{dB}. \tag{4}$$

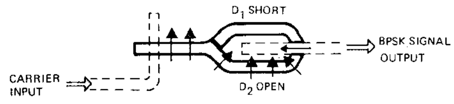
The calculated insertion loss at 60 GHz is about 0.8 dB and the isolation is over 15 dB.

Although the above calculations are approximated neglecting the package parasitics, it can be concluded that at 60 GHz the shunt-mounted structure has similar insertion loss compared to the series-mounted structure, but with much higher isolation. The experimental results confirmed this prediction.

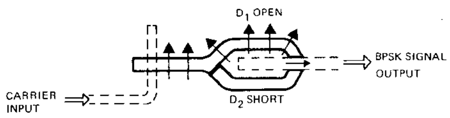
Our biphase switch design uses a minimum of components to accomplish biphase modulation with low loss and wide bandwidth. The balanced configuration provides good isolation between the input carrier and the modulated output port.

The biphase switch operates as follow. The 60-GHz signal at the microstrip input is transferred to the slotline via the microstrip–slotline transition. The bias states of the Schottky diodes then determine which path the signal takes as the data alternately switches the Schottky diodes on and off. The signal takes path 1 or path 2, producing a biphase output signal because the direction of the electric field at the output junction is 180 degrees out-of-phase, as shown in Fig. 6. A second slotline–microstrip transition is used to transfer the modulated 60-GHz modulated signal back to the microstrip medium.

The biphase switch was first built at 15 GHz and then scaled up to 60 GHz. Fig. 7 shows the performance of this 60-GHz biphase switch. Phase balance of less than ±3 degrees and amplitude balance of less than ±0.5 dB were achieved. The carrier suppression is over 20 dB for the modulated signal. The isolation can be measured by the control of bias level. With one diode "OFF," the leakage from one diode is illustrated in Fig. 8(a). With both diodes "OFF," the leakage from both diodes is shown in Fig. 8(b). The isolation from one diode is over 20 dB.

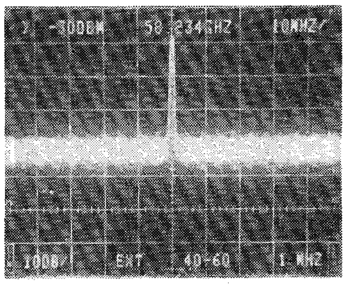


(a)

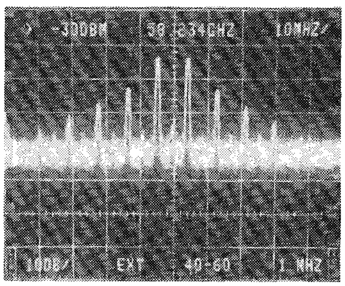


(b)

Fig. 6. Operating principle of biphase switch (a) with diode D_1, short and (b) with diode D_2 short.



(a)



(b)

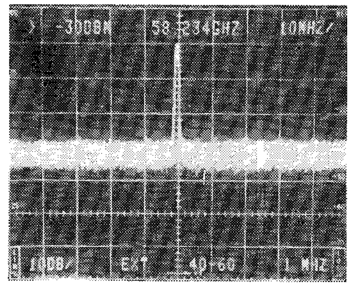
Fig. 7. 60-GHz biphase switch performance. (a) Unmodulated carrier. (b) 10-MHz modulation.

C. Slotline-to-Microstrip Transition

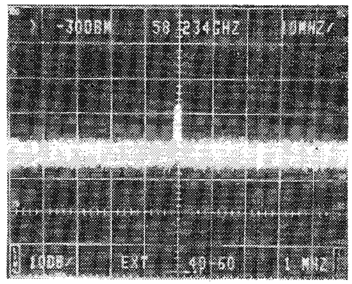
The design of a microstrip-to-slotline transition can be found in the literature [7], [8]. The slotline, etched on one side of the substrate, is crossed at a right angle by a microstrip conductor on the opposite side. The microstrip extends about one quarter of a wavelength beyond the slotline and, similarly, the slotline extends about one quarter of a wavelength beyond the microstrip. The microstrip is placed on one side of the substrate and the slotline on the other side. The transition thus makes two-level circuit design possible.

V. Performance

The QPSK modulator chip was integrated with the Gunn VCO, subharmonic mixer, directional coupler, and a microstrip-to-waveguide transition to form the RF exciter/modulator module. The modulated 60-GHz output power is coupled to a waveguide through a microstrip-to-waveguide transition. Fig. 9 shows the circuit board inside the



(a)



(b)

Fig. 8. Biphase switch isolation measurement (including leakage from both diodes). (a) Output carrier with one diode "OFF," and (b) output with both diodes "OFF."

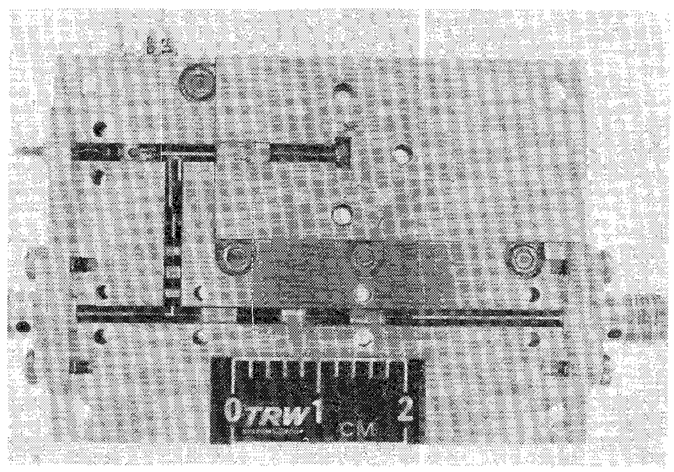


Fig. 9. RF exciter/modulator module.

housing. The unit has a volume of about 1.6 in^3 ($1.8 \times 2.5 \times 0.35$ in).

Both static and dynamic tests have been carried out to characterize the exciter/modulator. The static tests consist of phase and amplitude measurements, and insertion-loss and return-loss measurements. The dynamic tests consist of bit error rate (BER) measurements and data spectrum measurements.

The phase and amplitude measurements were carried out using a 60-GHz network analyzer modified to measure S_{21} parameters. A phase imbalance of less than ± 3 degrees and an amplitude imbalance of 0.5 dB was achieved.

The network analyzer gives absolute insertion loss of the device as well as the relative loss for each phase state. Insertion loss and return loss were measured from 58 to 62

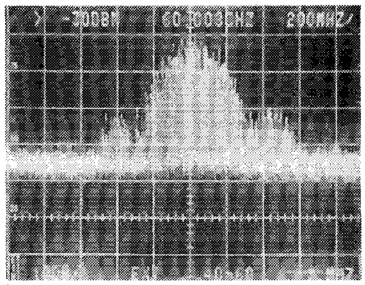


Fig. 10. Spectrum of modulated signal.

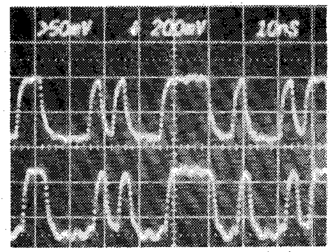


Fig. 11. QPSK waveforms. Top trace is modulating signal; bottom trace is demodulated output.

GHz. An insertion loss of 13.5 dB for the modulator and transition was achieved at 60 GHz and varied approximately 1.5 dB across the 4-GHz measurement bandwidth. Return loss at 60 GHz is 13 dB for the input port and 9.5 dB for the output port. The return loss is quite flat across the 4-GHz measurement bandwidth.

Fig. 10 shows the spectrum of a modulated signal. The spectrum is a result of modulating both the I and Q channels with the Tau-Tron BER test transmitters using the short code sequence (2^7-1 bits). The output spectrum was viewed directly with a V-band spectrum analyzer. The spectrum of an unmodulated signal can be found in Fig. 7(a) for comparison.

Fig. 11 compares the modulating waveform with the demodulated output. The modulating waveform was observed at the BER transmitter output. The demodulated signal was observed at the bit synchronizer output. An external delay was used in conjunction with the oscilloscope delay to allow a direct comparison of the modulating waveform and the demodulated output.

VI. Conclusions

A microstrip 60-GHz QPSK exciter/modulator was developed with state-of-the-art performance. The unit is very small and capable of handling wide-band, high data rates. The results have firmly established direct modulation techniques using integrated circuits at millimeter-wave frequencies.

Acknowledgment

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