High Data-Rate Solid-State Millimeter-Wave Transmitter Module

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Abstract—**This paper describes a solid-state millimeter-wave transmitter module consisting of an IMPATT oscillator, p-i-n quadriphase modulator, and a three-stage IMPATT amplifier. The module has been operated up to 4-Gbits/s modulation rate with 500-mW output power in the 60-GHz range.**

I. INTRODUCTION

COUPLED with the recent advancement of various solid-state millimeter-wave devices, a great deal of effort is now being directed toward the development of millimeter-wave systems. One of the major advantages of millimeter-wave communication systems is that broad bandwidths can be achieved relatively easily. Thus very high data-transmission rates are feasible at millimeter-wave frequencies. This paper describes the development of a solid-state millimeter-wave transmitter module that has been operated successfully at modulation rates up to 4 Gbits/s, demonstrating the feasibility of gigabit data rates in the 60-GHz range. System design consideration and the development of new devices and components needed for the system are described in detail. The module consists of an IMPATT oscillator, a two-stage p-i-n-diode quadriphase modulator, and a three-stage IMPATT amplifier including a hybrid-coupled power amplifier/combiner capable of 500-mW CW output power.

II. MODULE DESIGN CONSIDERATIONS

Various configurations possible for phase-shift-keying (PSK) millimeter-wave transmitter modules are shown in Fig. 1. The first approach is an oscillator followed by a phase modulator [1]. This configuration, though it offers simplicity, has two major disadvantages: 1) the modulator must be capable of operating at the full RF power, and 2) the output power will be reduced by the amount of insertion loss of the modulator from the maximum available with a given device. These limitations can be removed by adding an amplifier at the output stage, as shown in Fig. 1(b) and (c). The power amplification of phase-modulated signals can be accomplished with either a stabilized amplifier or an injection-locked oscillator [2]–[4]. However, for a given device, a greater gain–bandwidth product can be obtained with a stabilized amplifier than with an injection-locked oscillator [2], [3].

A quadriphase modulation can be accomplished by combining two biphase modulators in various ways [5]–[8], as shown in Fig. 2. The series connection is the simplest in construction and yields the lowest insertion loss.

Based on these design considerations, we have selected to develop a module as shown in Fig. 3. It consists of an IMPATT oscillator, a two-stage circulator-coupled p-i-n-diode quadriphase modulator, and a three-stage IMPATT amplifier. The IMPATT amplifier consists of two circulator-coupled amplifiers and a hybrid-coupled power amplifier/combiner. Shown in Fig. 4 is a photograph of the module.

III. PHASE MODULATOR

For the high data-rate millimeter-wave phase modulation, either a p-i-n-diode modulator or a varactor modulator can be used. The phase modulation is achieved by switching the bias to change the diode impedance between a high-impedance state and a low-impedance state. The principle of the phase-modulator operation is demonstrated in Fig. 5. The design of a phase modulator is primarily determined by three factors: 1) insertion loss; 2) phase-switching speed; and 3) power-handling capacity. In order to achieve low insertion loss and high switching speed, the diode-junction geometry must be made very small. However, in order to achieve high power-handling capacity, the diode junction should be made large. By using the amplifier at the output stage as discussed in the preceding section, the modulator need not handle high RF power.

In terms of insertion loss, a figure of merit Q (a measure of diode quality) for a diode to be used is given by [7]

$$Q = \left[\frac{(R_1 - R_2)^2 + (X_1 - X_2)^2}{R_1 R_2}\right]^{1/2}$$

where R and X are, respectively, the real and imaginary parts of the diode RF impedance and the subscripts 1 and 2 refer to the two bias states. In order to achieve low insertion loss, Q must be maximized by minimizing the series resistance and maximizing the reactance. For this reason, the junction capacitance should be minimized.

In a p-i-n-diode phase modulator, the modulation is accomplished by switching the diode between a forward-

Manuscript received September 23, 1974; revised January 30, 1975. This work was supported by the U. S. Air Force Avionics Laboratory, Wright-Patterson Air Force Base, Ohio, under Contract F33615-73-C-1106.

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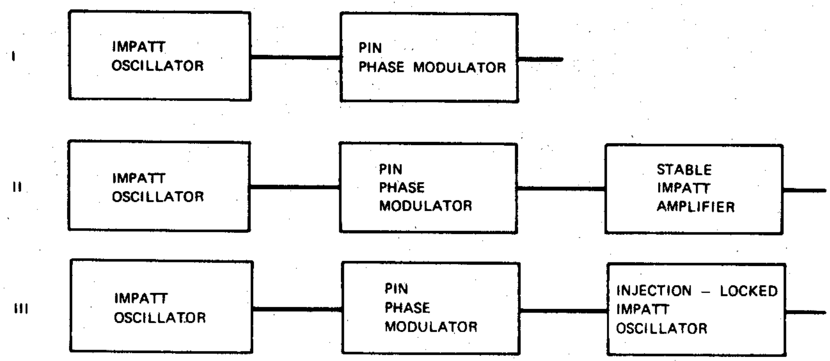
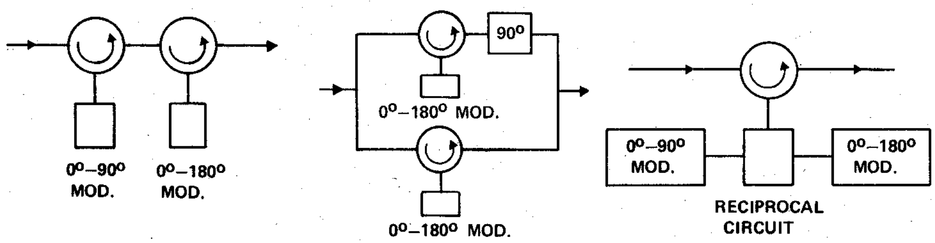


Fig. 1. Various approaches to millimeter-wave PSK transmitter-modules.



(a) (b) (c)

Fig. 2. Quadriphase modulator configurations. (a) Series-connection configuration. (b) Parallel-connection configuration. (c) Single circulator–reciprocal circuit configuration.

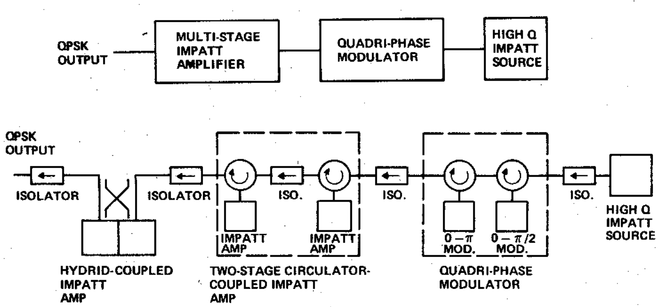


Fig. 3. Block diagram of millimeter-wave *Q*-PSK transmitter module.

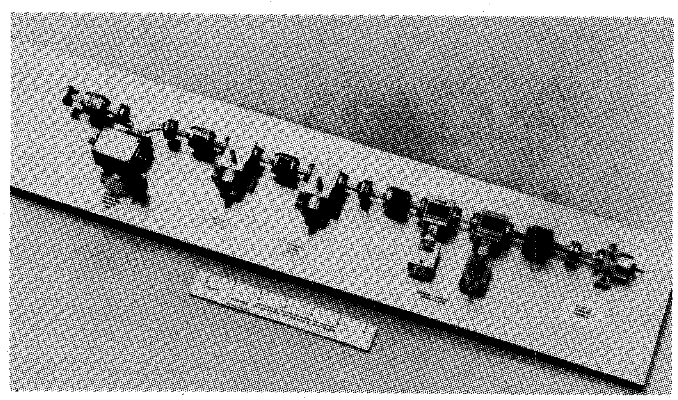


Fig. 4. Photograph of millimeter-wave *Q*-PSK transmitter module.

bias state, where the RF impedance is very low, and a reverse-bias state, where the RF impedance (reactance) is high. In a varactor phase modulator the diode is switched between a low reverse voltage, where the RF impedance (reactance) is relatively low, and a high reverse voltage, where the RF impedance (reactance) is relatively high. It is easier to achieve high Q and a low insertion loss with a p-i-n-diode phase modulator than with a varactor phase modulator. This is mainly due to the fact that both the series resistance and the capacitance of a varactor are relatively large at a low reverse-bias voltage. In addition, a sharp phase transition takes place in a p-i-n-diode modulator near the zero-bias point, whereas the phase transition is gradual in a varactor modulator. This sharp phase transition in a p-i-n-diode phase modulator results in a fast phase-switching time. For these reasons, we have chosen p-i-n-diode phase modulators for the module.

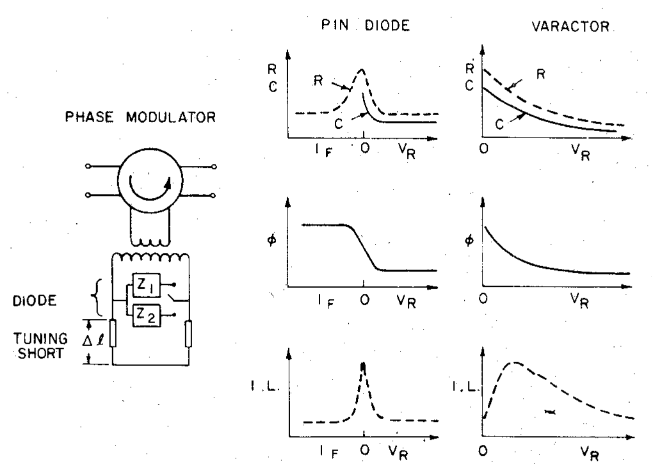
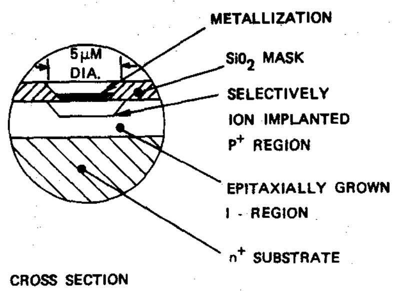
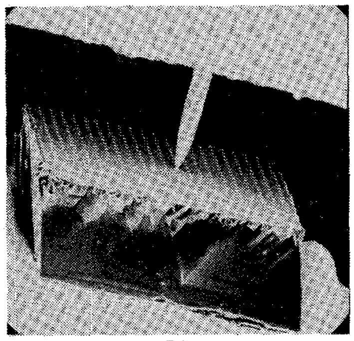


Fig. 5. Operational principle for p-i-n diode and varactor phase modulators.



(a)



(b)

Fig. 6. Ion-implanted planar p-i-n-diode structure for high data-rate millimeter-wave phase modulators. (a) P-i-n-diode structure. (b) Diode mount and bias contact.

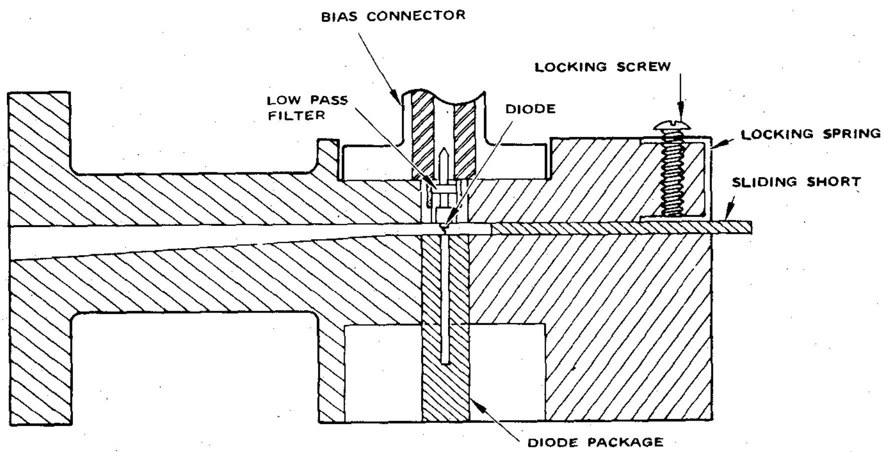


Fig. 7. Cross-sectional view of millimeter-wave phase modulator.

The phase transition time of a modulator that determines the upper data transmission rate is mainly determined by the diode switching speed. The switching time of a p-i-n-diode is related to a time constant $\tau_F = W^2/2D$ where W is the I-region thickness and D is the carrier diffusion coefficient. In order to achieve subnanosecond switching time, the I-region thickness is required to be in the order of 1 μm. The junction capacitance of the diode at the reverse-bias voltage is determined by $C_j = \epsilon A/W$, where ϵ is the dielectric constant and A is the junction area. Thus, in order to obtain a relatively large impedance at a millimeter-wave frequency with a diode having a very thin I-region, the junction area must be made very small.

In order to achieve both a low insertion loss and a fast switching speed, we have developed planar ion-implanted p-i-n diodes with extremely small junctions (5-μm diameter), as shown in Fig. 6. The junction is formed by selectively ion-implanting borons through holes in an SiO_2 mask into an epitaxially grown high-resistivity layer on a low-resistivity n^+-type silicon substrate. A diode chip with an array of small junctions is mounted in a wafer-type mount with a reduced-height waveguide section. The electrical contact is made by means of an electrochemically etched AuNi whisker. A cross-sectional view of the phase modulator is shown in Fig. 7. Phase modulation is tuned by adjusting the position of the movable short placed behind the diode, as shown in the figure. In addition, in order to

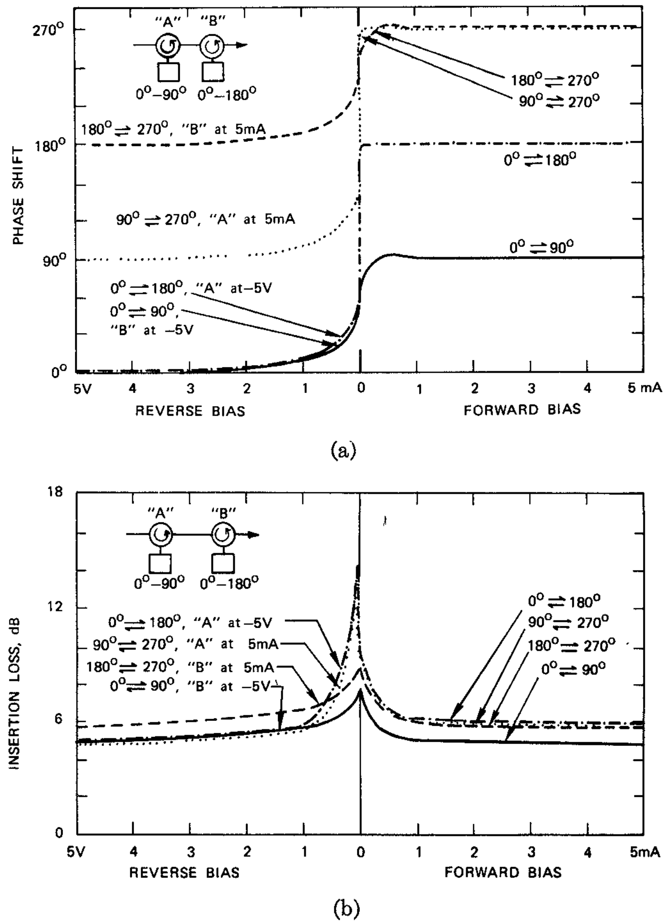


Fig. 8. Phase transition characteristics and insertion-loss variations of p-i-n-diode quadriphase modulator. (a) Phase transition. (b) Insertion loss.

achieve the desired amount of phase shift with balanced insertion loss, an optimum whisker length was empirically determined.

A quadriphase modulator was constructed by combining a 90° phase modulator and a 180° phase modulator connected in series. Phase-transition characteristics and insertion-loss variations of the quadriphase modulator measured with a phase bridge are shown in Fig. 8 as a function of the bias applied to the diode. The measurements were taken by varying the bias applied to one of the two diodes while keeping the other diode at a fixed bias state. In this way, four possible combinations of phase transitions were generated; viz., 0°–90°, 0°–180°, 90°–180°, and 90°–180°. Phase transitions shown in Fig. 8 reveal that the transitions are abrupt with more than 90 percent of the phase shift occurring within a narrow bias region between 1-V reverse voltage and 0.1-mA forward current. The sharpness of the phase transitions effectively enhances the phase-modulation speed. The total insertion loss of the two-stage modulator was measured between 5 and 6 dB when operated between 5-V reverse bias and 5-mA forward bias. These low bias current and voltage requirements for the modulator are an additional important feature for the construction of transistorized subnanosecond bias drivers to achieve high modulation rates.

The switching response of the quadriphase modulator was evaluated by means of a quadriphase bridge, as shown in Fig. 9. Two pulse generators were used as bias drivers for the phase modulators. By adjusting the pulsewidth and the relative position of the pulses, various simulated data patterns were generated. The phase modulation was detected by comparing the phase with two references; one set at +45° and the other at −45°, as shown in the figure [8]. Shown in Fig. 10 are data pulse trains detected at the two reference arms. Fig. 10(a) shows the pulse trains obtained with the modulator operated at a modulation rate of 2 Gbits/s. Those shown in Fig. 10(b) were obtained with the modulator operated at 4 Gbits/s. A phase transition time of 0.4 ns was measured.

IV. IMPATT OSCILLATOR AND AMPLIFIER

An IMPATT diode can be used as an oscillator or an amplifier. The frequency generation was accomplished by directly generating millimeter-wave power with a free-running IMPATT oscillator. The IMPATT oscillator was tuned for a high-Q condition rather than for a high output power

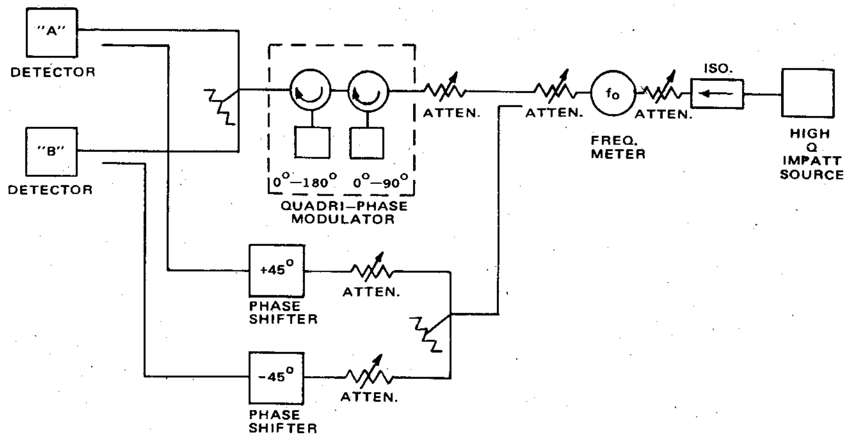
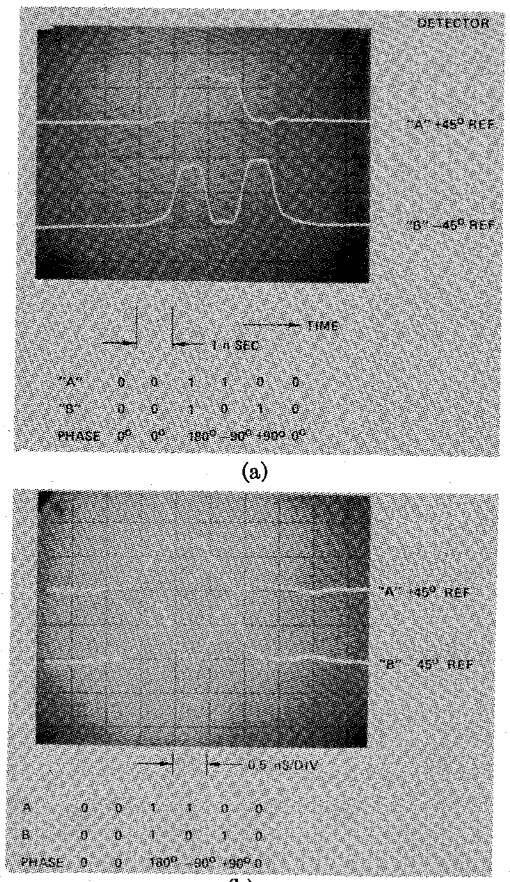


Fig. 9. Coherent phase bridge for quadriphase modulator evaluation.



(a)

(b)

Fig. 10. Data pulse trains generated by quadriphase modulator detected with phase bridge. (a) 2-Gbits/s modulation rate. (b) 4-Gbits/s modulation rate.

to minimize noise. The double sideband signal-to-noise ratio of 120 dB has been measured with 1-kHz receiver bandwidth at 50-kHz modulation frequency from a silicon IMPATT oscillator in the 60-GHz range [12].

It has been shown that IMPATT amplifiers can be used effectively for power amplifications of phase-modulated signals at millimeter-wave frequencies [2], [3], [9]–[11]. An IMPATT diode can be operated either as a stabilized amplifier or an injection-locked oscillator by adjusting the tuning conditions. With a given IMPATT diode, the stabilized amplifier and the injection-locked oscillator can produce approximately the same saturated output power level [2], [3]. Both types of amplifier can be used for the power amplification of phase-modulated signals. However, the injection-locked oscillator is suited for a relatively high-gain narrow-band amplification, whereas the stabilized amplifier is suited for a relatively broad-band amplification [2], [3]. Thus the stabilized amplifier is a better choice for a high data-rate application. The full bandwidth $2\Delta f$ required for the amplification of phase-modulated signals with phase-switching time T_s is given by [2]

$$2\Delta f > T_s^{-1}.$$

Thus, for the signals with 0.4-ns switching time, the required amplifier bandwidth is 2.5 GHz.

The RF performance of an IMPATT diode is strongly related to its dc characteristics. For the present transmitter module, P^+-n-n^+-type single-drift silicon IMPATT diodes were used. The breakdown voltage of the diode used is typically 16 V, which is an optimum value for the 60-GHz range [3]. The diodes are sealed in subminiature quartz-ring packages with extremely small parasitics [12].

Shown in Fig. 11 is a cross-sectional view of the amplifier circuit. An IMPATT-diode package is mounted in a reduced-height waveguide section. A quarter-wavelength impedance transformer is used between the reduced-height and full-height waveguide sections. This circuit possesses a unique feature of providing 2 deg of freedom in tuning by means of an adjustable coaxial section placed in series with the diode and a movable short placed in parallel with the diode [3]. In this way, both the real and imaginary components of the circuit impedance can be matched to those of the diode to obtain an optimum performance at a desired frequency.

The amplifier consists of a two-stage circulator-coupled amplifier and a hybrid-coupled power amplifier/combiner [13]. The circulators developed for the amplifiers were tuned to have high isolation and low standing-wave ratio (SWR) over a broad bandwidth. In addition, a special effort was directed to minimize the SWR outside the

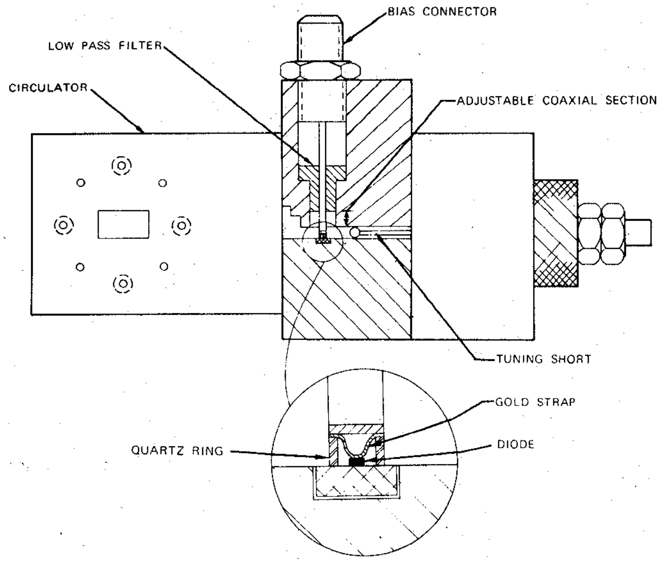


Fig. 11. Cross-sectional view of IMPATT amplifier circuit.

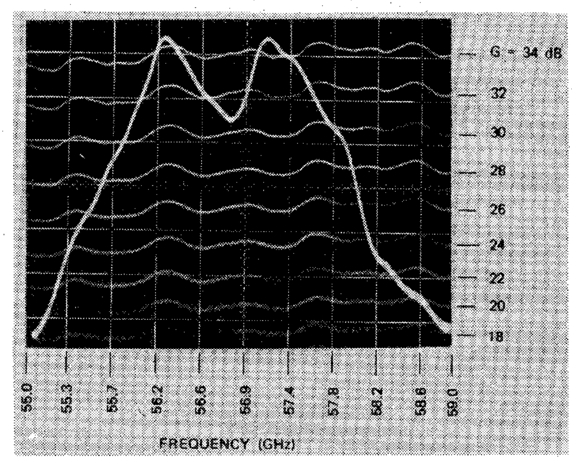


Fig. 12. Bandpass characteristics of three-stage IMPATT amplifier.

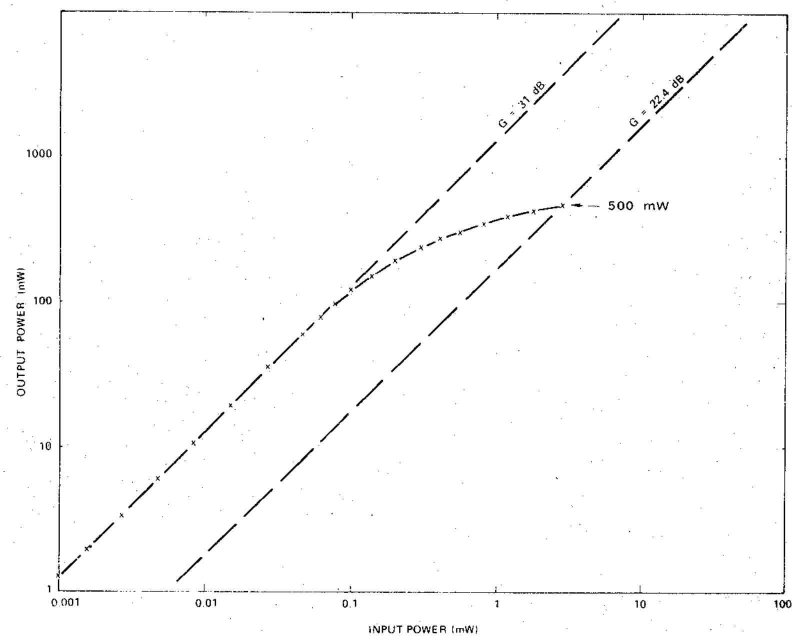


Fig. 13. Power-transfer characteristics of three-stage IMPATT amplifier.

band of interest so that the reflection from the circulator would not cause spurious oscillations outside the amplifier passband. Isolations greater than 20 dB, insertion losses less than 0.3 dB, and SWR less than 1.2:1 have been obtained over a 3.5-GHz bandwidth in the 60-GHz range. Outside the band SWR was measured to be less than 1.5:1 over the entire *V* band (50–75 GHz). The hybrid coupler used was a short-slot side-wall coupler. It has an isolation greater than 30 dB, and insertion loss less than 1 dB, and the coupling unbalance less than 0.25 dB over a 10-GHz bandwidth. In order to achieve additional interstage isolations, broad-band isolators were used. The Faraday rotation-type isolator used in the module provides an isolation greater than 30 dB and an insertion loss less than 1 dB over the entire *V* band.

With the two-stage circulator-coupled amplifier, a small-signal gain of 21 dB, and a small-signal 3-dB bandwidth of 3.5 GHz have been achieved. At a power-saturation point, output power of 180 mW was obtained with 14-dB gain. With the hybrid-coupled amplifier, a small-signal gain of 12 dB, a 3-dB bandwidth of 5.8 GHz, and a saturated output power of 500 mW have been obtained. The two-stage circulator-coupled amplifier and the hybrid-coupled amplifier were then combined. Shown in Figs. 12 and 13, are, respectively, the bandpass characteristics and the output versus input transfer characteristics of the three-stage amplifier. An overall gain of 31 dB and a small-signal bandwidth of 3.0 GHz have been obtained. At a saturation point, output power of 500 mW with 22-dB gain and 3.5-GHz bandwidth has been obtained. This bandwidth is sufficient to amplify *Q*-PSK signals with a data rate up to 7 Gbits/s.

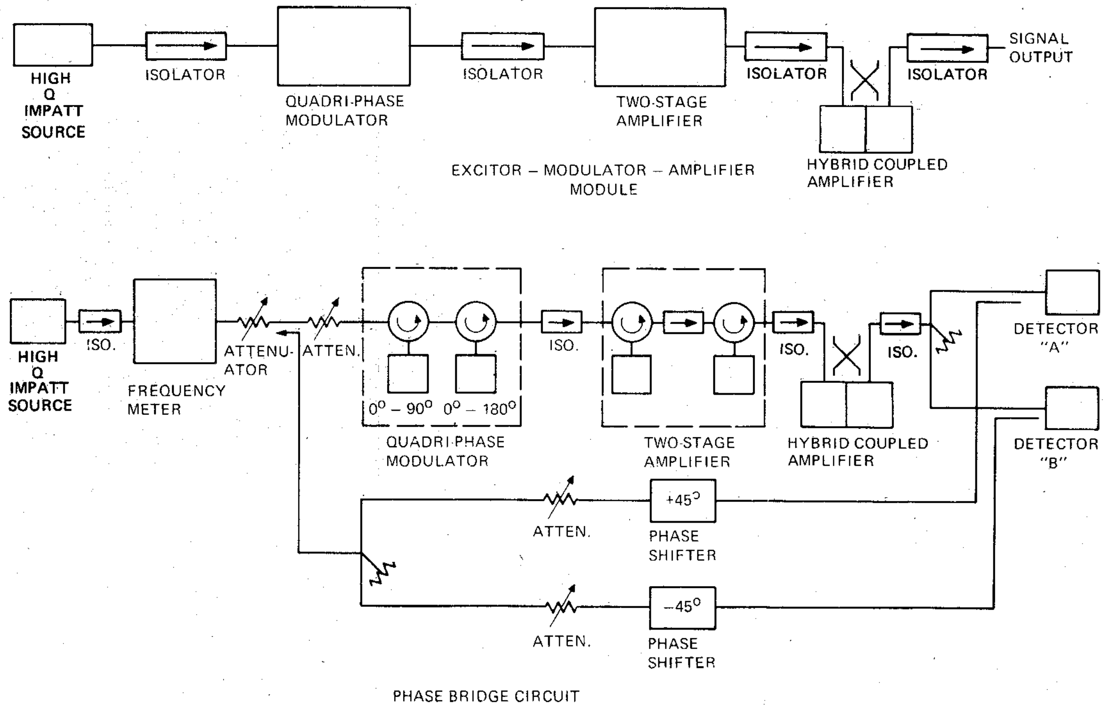


Fig. 14. Differentially coherent phase bridge for Q-PSK signal detection.

V. TRANSMITTER MODULE

A transmitter module as shown in Fig. 4 was constructed by combining an IMPATT oscillator, a quadriphase modulator, and a three-stage IMPATT amplifier, which was described in the preceding sections. An isolator was used at each interphase to minimize spurious responses that may be caused by interstage mismatch. In order to evaluate the module, a coherent phase bridge [8] for Q-PSK signal as shown in Fig. 14 was constructed. Various simulated data patterns were generated by means of two-pulse generators by the technique used for the evaluation of the phase modulator. Data pulse trains generated by the transmitter module and detected by the differential phase bridge are shown in Fig. 15. They were obtained with the module operated at a 2-Gbits/s data rate. In order to determine the upper limit of the modulation rate, the transmitter module was operated at increased modulation rates. It was successfully operated at a modulation rate corresponding to 4 Gbits/s.

VI. CONCLUSIONS

In the preceding sections, the development of a solid-state transmitter module consisting of an IMPATT oscillator, p-i-n quadriphase modulator, and a three-stage IMPATT amplifier including a hybrid-coupled power amplifier/combiner stage was presented. Both system design considerations and components development were described in detail. Test and evaluation of each component and the system performance were presented. The module has been operated successfully for generating quadriphase-modulated signals at a data rate up to 4 Gbits/s with 500-mW

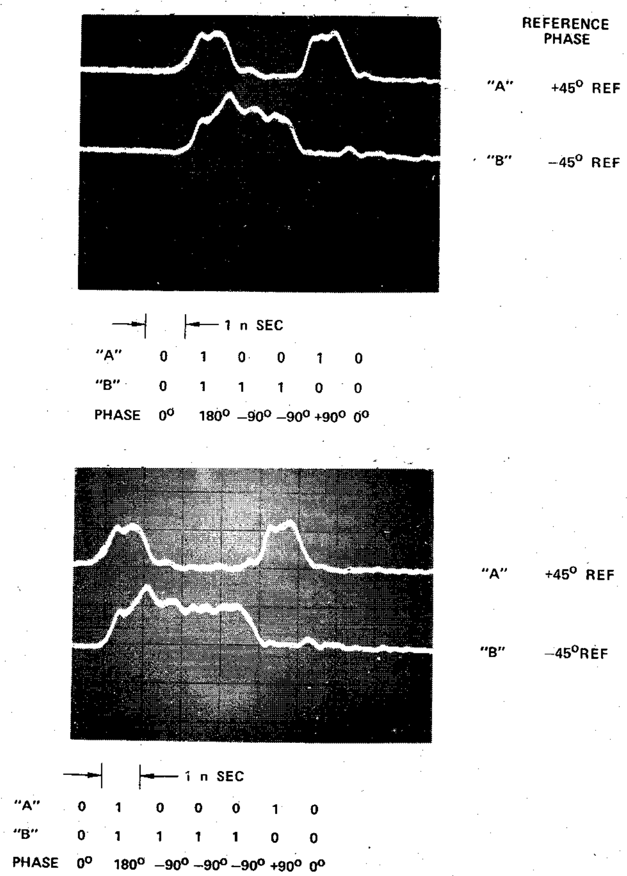


Fig. 15. Data pulse trains from millimeter-wave transmitter module detected by differentially coherent phase bridge.

output power in the 60-GHz range. The results achieved with the module have demonstrated the feasibility of an all-solid-state millimeter-wave transmitter module capable of a data rate greater than 1 Gbit/s. The output power may further be increased by means of combining a larger number of diodes and the use of double-drift IMPATT diodes capable of higher output power [14].

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Frequency Multiplication by a P-I-N Diode When Driven into Avalanche Breakdown

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***Abstract*—An investigation of frequency multiplication using a step-recovery diode (SRD) driven into avalanche breakdown is presented. This mode of operation, which is called the "breakdown mode," consists of a reverse-biased p-n junction, SRD, or IMPATT diode driven into reverse breakdown by an ac signal source. As the diode voltage passes from reverse bias to reverse breakdown and avalanche, the state of the diode switches quickly from a depletion-layer capacitance to an avalanche inductance; hence the production of strong harmonics. A theoretical analysis and experimental investigation of a coaxial/waveguide 2–6-GHz frequency multiplier using HP5082-0320 step-recovery diodes, [$R_S = 0.75\ \Omega$, $C_d(-6v) = 1.0$ pF] shows that the breakdown-mode frequency multiplier has a higher conversion efficiency than the conventional "charge-storage" multiplier. A measured conversion efficiency of 73 percent was achieved while the *same circuit* configuration produced 52 percent for the *same* diode used as a charge-storage multiplier under optimum forward-drive and tuning conditions. Also the theory developed in this paper indicates a maximum possible conversion efficiency of 80 percent for the breakdown-mode multiplier, which corresponds closely with the measured results, and a maximum theoretical efficiency for a forward-driven diode of 64 percent. The performance of an FM microwave system was monitored using the breakdown multiplier as a LO in which a baseband SNR of 59 dB was recorded.**

Manuscript received August 27, 1974; revised January 27, 1975. This research was jointly supported by Carleton University and by National Research Council Grant N.R.C. 2056-87-A8447.

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I. INTRODUCTION

VARACTOR frequency multipliers have progressed from the work of Penfield and Rafuse [1] with nominally driven abrupt junction-diodes to the general analysis and design of varactor frequency multipliers with the arbitrary capacitance variation and drive level by Burckhardt [2], Scanlan [3], and others.

The overdriven stored-charge multiplier is characterized by high efficiency, decreasing with the order of multiplica-