11-GHz MIC QPSK Modulator for Regenerative Satellite Repeater

GERHARD OHM AND MICHAEL ALBERTY

***Abstract*—An 11-GHz MIC QPSK modulator for a 14/11-GHz, 120-Mbit/s regenerative satellite repeater is described. The modulator consists of cascaded 90° and 180° phase switches, realized with circulators and PIN diodes. The static and the dynamic behavior are presented. It is shown how the bit-error-rate performance is deteriorated by slow switching transients and timing errors.**

I. Introduction

FUTURE communications satellites will employ high-capacity transmission links applying digital phase modulation (PSK) and time-division multiple access (TDMA) of the transponder. In such complex systems, regenerative satellite repeaters demodulating the received PSK signal, regenerating the baseband signal, and remodulating an RF carrier offer some advantages compared to the still used transparent transponders [1]–[4].

The present paper describes an 11-GHz MIC QPSK modulator as part of 14/11-GHz, 120-Mbit/s regenerative satellite repeater which has been designed for possible use in the European Communications Satellite System (ECS) [5]. Because of its simplicity and reliability, the switched-type modulator with circulators has been adopted consisting of cascaded 90° and 180° phase switches. The design considerations leading to this approach are described, particularly with respect to space requirements. Besides the static behavior, the dynamic performance which is known to be critical with the serial-type modulator [6]–[9] is treated. It is shown how strong the bit-error-rate performance is affected by switching time and timing errors.

II. General Design Considerations

For the strongly nonlinear downlink of a satellite system, the switched-type modulator operating directly at the transmit frequency was found to be the simplest approach [5], [10]. The switched-type modulator instantly shifts the carrier phase to the desired values while maintaining a constant carrier amplitude. In the case of quarternary phase shift keying (QPSK), which is considered here, modulation is normally accomplished by combining two binary phase switches.

The binary phase switches can be connected in series or in parallel to obtain the four phase values of the QPSK modulator (0, 90°, 180°, 270°). With the parallel arrangement, however, 3-dB insertion loss occurs due to the orthogonal combination of the two 180° switches.

According to their realization, phase switches can be divided into two classes: reflection type and transmission type. Reflection-type phase switches consist either of a circulator with one reflecting element or of a hybrid with two reflecting elements. Normally, switching diodes are used for the signal reflection. Transmission-type phase switches, on the contrary, connect the carrier via different path lengths to the output. Transistors, especially dual-gate FETs, are well suited as switching elements for this application [11].

Comparing the above-sketched modulator types with respect to space application one has to consider reliability, power consumption, size, and weight. The reflection-type modulator consisting of cascaded phase switches with circulators requires only two microwave switching elements and can be implemented with limited size and weight. Therefore, this approach is most suitable for satellite use, and has been chosen for implementation.

For the selection of the switching elements the driver circuits also have to be considered. Whereas Schottky diodes can be driven directly by the complementary outputs of an ECL circuit (± 0.8 V), PIN diodes need special driver circuits. However, due to the low-power capability of Schottky diodes [5], PIN diodes have to be used at the required output level of greater 0 dBm. Although it seems possible in principle to drive PIN diodes with very thin intrinsic layers directly by ECL circuits, available fast switching PIN diodes require higher reverse voltages to achieve short off-transition times. With a low reverse bias the initial fast off transition is followed by small phase and amplitude variations causing increased bit-error rates.

III. Modulator Design

The principle structure of the modulator developed is shown in Fig. 1. Each phase switch consists of a circulator, a transformation network, a PIN diode, and a driver circuit. Design and function of the phase switches and the composite modulator are described in the following sections.

A. *Microwave Circuit*

The function of the transformation network is to transform the diode reflection coefficients of the forward and

Manuscript received March 10, 1982; revised June 2, 1982. This work was supported in part by the Bundesminister für Forschung und Technologie under Contract 01 TH 068-AK/RT/WRT 2078. However, the responsibility for the content lies solely with the authors.

The authors are with AEG-Telefunken Nachrichtentechnik GmbH, Space Communications System Division, Gerberstrasse 33, D-7150 Backnang, West Germany.

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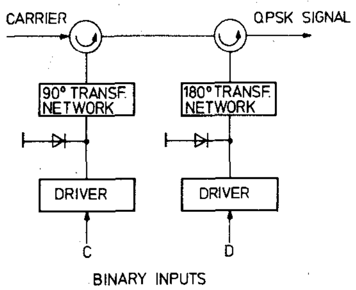


Fig. 1. Modulator schematic diagram.

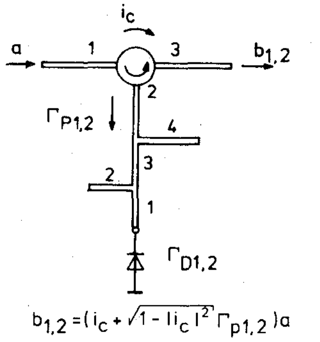


Fig. 2. Principle structure of the phase switches.

reverse bias condition Γ_{D1} and Γ_{D2}, respectively, in a way that the transmission coefficients $T_{1,2} = b_{1,2}/a$ of the phase switch (Fig. 2) are of equal magnitude but distinct phase differences

$$|T_1| = |T_2|$$
$$\arg(T_1) - \arg(T_2) = \Delta\varphi = 90°, \qquad 180°. \tag{1}$$

Also, in case of an ideal circulator, the reflection coefficients $\Gamma_{P1,2}$ have to fulfil (1). However, due to the finite isolation in practice a part i_c of the input signal flows directly from port 1 to 3. Therefore, the actual transmission coefficients are given by

$$T_{1,2} = i_c + \sqrt{1-|i_c|^2}\,\Gamma_{P1,2} \tag{2}$$

and differ from $\Gamma_{P1,2}$.

Fig. 2 shows the structure of the transformation network used in both phase switches. It is realized in microstrip technique and uses two stubs and two series line sections for impedance transformation. For the network design, a computer program has been established which allows circuit optimization for minimum phase and amplitude deviation within a defined frequency band. The program can also take account of the finite circulator isolation. In the present application, however, where the phase and amplitude of i_c vary strongly from device to device, it is hardly possible to find appropriate values for the calculations. Therefore, the transformation networks have been optimized considering ideal circulators.

With the PIN Diode ND 6651-3G (NEC), optimized networks with the structure of Fig. 2 yield broad-band phase switches which could be used in the entire satellite band from 10.95 to 11.7 GHz. The computed phase and amplitude variations remain below 1° and 0.3 dB, respectively, within that bandwidth for both the 90° and the 180° phase switch. When the network is adjusted with the stub length to compensate for the finite isolation, however, the phase switches become narrow-banded. With an isolation of 20 dB, the phase switches can only be adjusted by the stubs for one of the 83.3-MHz spaced channels. Since there are no requirements for multichannel operation, no attempt was made to achieve a broader bandwidth by use of additional tuning elements. Fig. 3 shows a photograph of the composite modulator. The transformation networks are realized on 25-mil alumina substrates. The stubs are slotted and extended by two rows of metallized areas. The slots are bridged and the metallized areas are interconnected by means of bond wires. Disconnecting bond wires then allows easy circuit tuning. With the slots causing a line extension, extremely fine tuning can be performed.

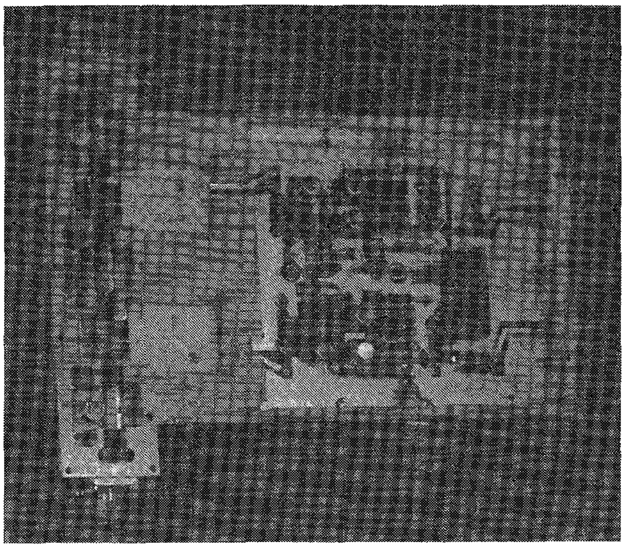


Fig. 3. Modulator assembly.

The circulators are drop-in devices realized on ferrite substrate. In order to avoid interaction between the switches caused by finite isolation of their circulators, an isolator is inserted between the two switches. Additional isolators are placed at the input and output ports to prevent phase and amplitude deviations by outer mismatch. The circulators and isolators are interconnected by microstrip lines on PTFE substrates (RT Duroid) which also carry matching elements to improve circulator and isolator performance.

B. Driver Circuit

The driver circuits have to amplify and transform the digital ECL signals so that the PIN diodes perform sufficient short switching times. Large current peaks are necessary to quickly inject the charge carriers into the diode intrinsic layer and to quickly remove them again.

Fig. 4 shows a driver circuit with a minimum number of semiconductor devices. Transistor $TS1$ and the output transistor of the ECL line receiver ($IC1$) form a differential amplifier for driving the final stage with transistor $TS2$. The inductance $L1$ is used to speed up the inherently slow diode off transition. With the aid of resistors $R8$ and $R9$ the static diode forward current is adjusted to about 1.5 mA.

To reduce parasitic elements, the driver has been realized

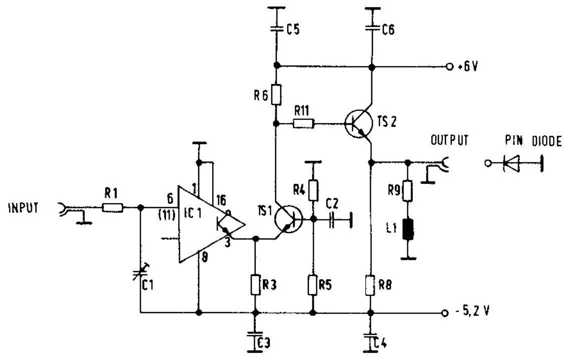


Fig. 4. PIN diode driver.

with chip resistors and capacitors, and with microwave transistors (NE 982, NEC). For comparison purposes, however, a second version has been constructed using conventional circuit components and UHF transistors (BFS 55 A). This driver is shown in the photograph of Fig. 3. Besides the different component technology, the driver uses an external transistor in the differential amplifier. Although the transition times with the second driver version are only 30-percent higher than with the first version, the bit-error rates differ significantly, as shown in the next section.

IV. Modulator Performance

Depending on the digital driving signals C and D, the modulator has to perform phase shifts of $\Delta\varphi = 0°$, $90°$, $180°$, and $270°$ with a vanishing amplitude difference $\Delta a = 0$. If $C = D = 0$ is chosen as a reference state ($\Delta\varphi = 0°$), the present modulator produces phase shifts of $\Delta\varphi = -90°$ with $C = 1$ and $\Delta\varphi = \pm 180°$ with $D = 1$.

A. Static Behavior

The modulator has been aligned at a midband frequency of 11.575 GHz with the aid of an automatic network analyzer. By disconnecting bond wires the four phase states could be adjusted to $\pm 0.1°$ with a maximum amplitude imbalance of ± 0.15 dB.

Fig. 5 shows the temperature dependence of both the phase and amplitude differences. In the specified temperature range from 10 to 40°C, the maximum phase deviation $\Delta\varphi(T_A) - \Delta\varphi(25°C)$ reaches about 2°. The different phase shifts are mainly caused by the circulators. The maximum amplitude imbalance is below 0.2 dB.

At both ports the return loss is greater than 20 dB in the entire satellite band from 10.95 to 11.7 GHz. Insertion loss amounts to 3.5 dB.

B. Dynamic Behavior

The dynamic behavior of a modulator is best examined by its demodulated output signal. Fig. 6 shows a block diagram of the measurement setup used for the dynamic measurements.

When evaluating the displayed output one has to consider that the phase detector detects both the amplitude and the phase difference. Approximately, the detector output is given by [12]

$$V \sim A(t) \sin \varphi_D(t) \tag{3}$$

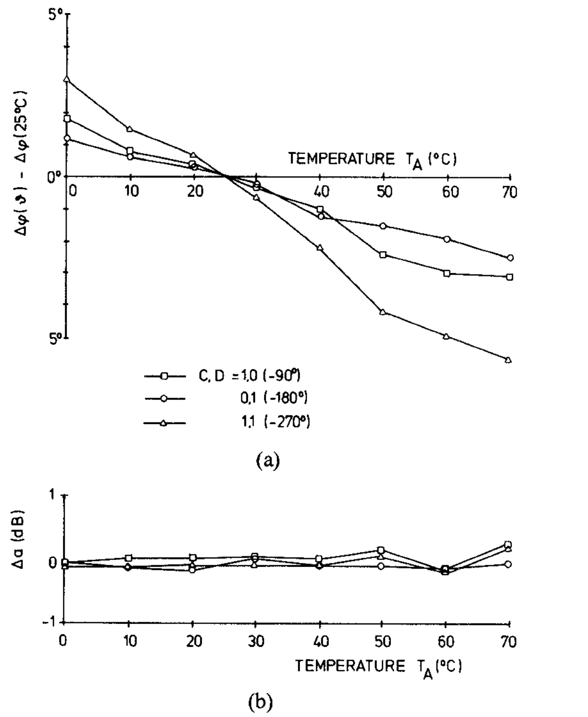


Fig. 5. Phase and amplitude deviation with temperature. (a) Phase deviation referred to 25° C. (b) Amplitude deviation, absolute.

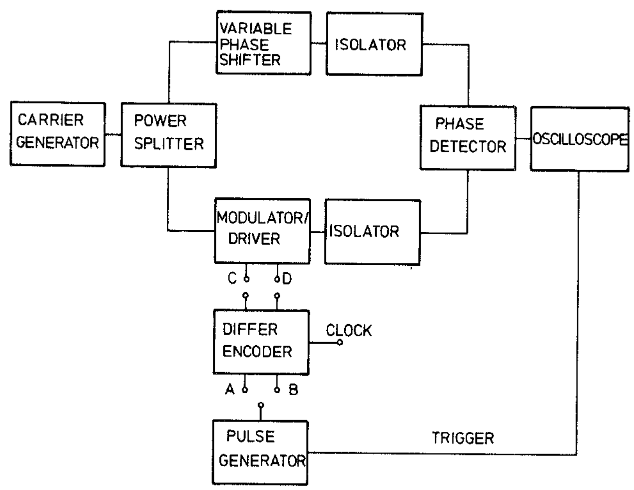


Fig. 6. Block diagram of measuring setup for dynamic measurements.

where $\varphi_D(t)$ is the phase difference between the detector input ports, and $A(t)$ is the input amplitude. With the phase adjuster, a proper operating point on the detector characteristic can be chosen. It is obvious from (3) that there are operating points where the phase detector is more sensitive to either phase or amplitude transitions.

The following displays were taken with two different phase shifter adjustments. With the adjustments chosen, the waveforms are given by

$$V \sim -A(t) \sin \begin{cases} \Delta\varphi(t) + 45° & \text{for} \quad 90° \text{ switch} \\ \Delta\varphi(t) + 90° & \phantom{\text{for}} \quad 180° \text{ switch} \end{cases} \tag{4}$$

for the displays of Fig. 7, and

$$V \sim -A(t) \sin [\Delta\varphi(t)] \tag{5}$$

for the displays of Figs. 8 and 9, where $\Delta\varphi$ is the phase difference as defined before.

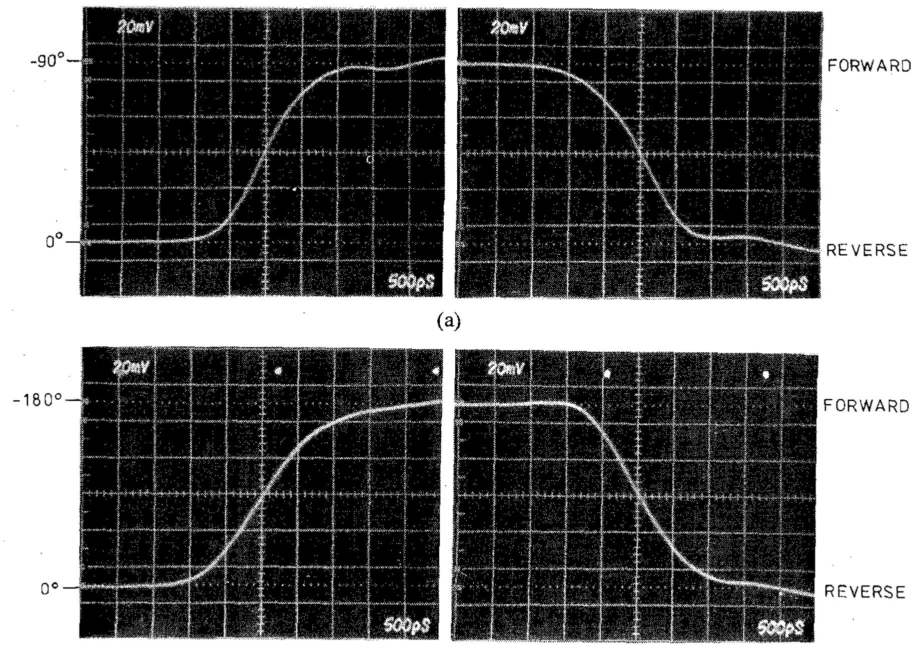


Fig. 7. Modulator rise and fall times with driver version (A). (a) 90° switch. (b) 180° switch.

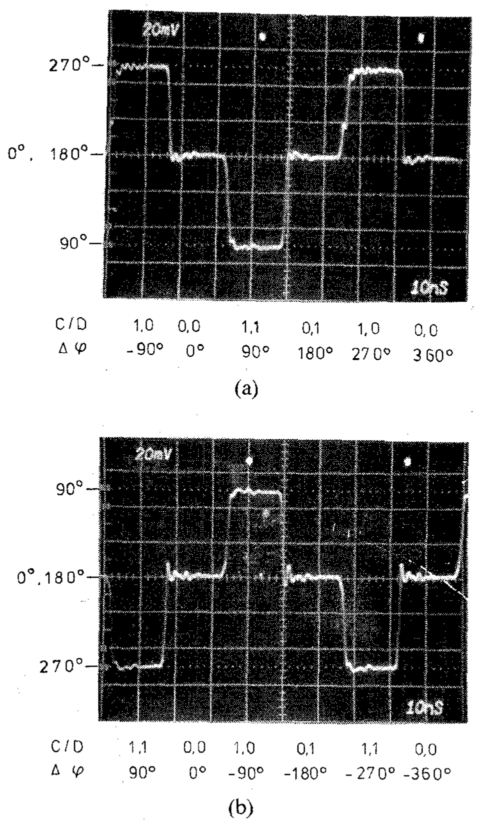


Fig. 8. Modulator output with driver version (A). (a) +90° sequence. (b) −90° sequence.

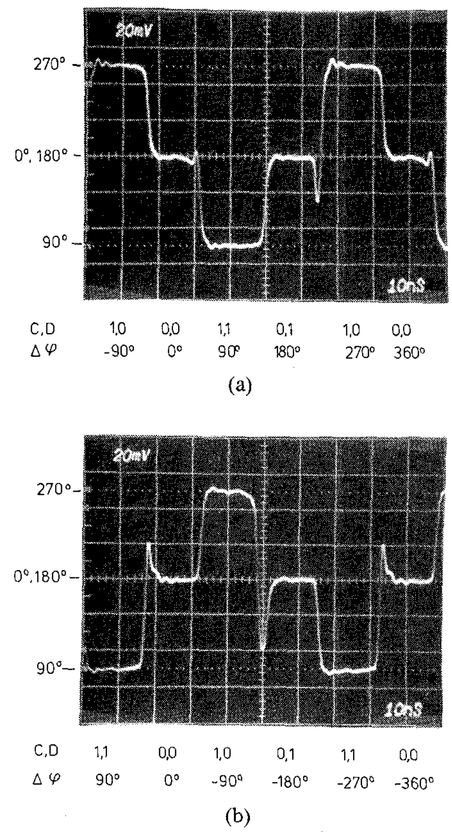
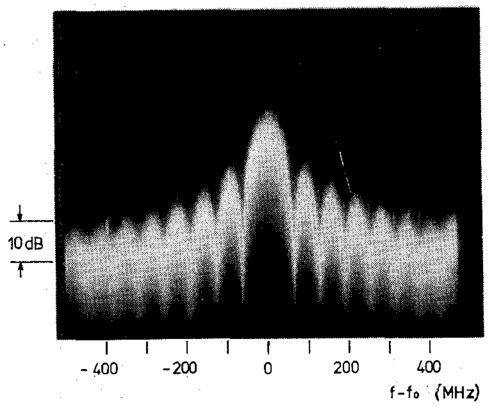


Fig. 9. Modulator output with driver version (B). (a) +90° sequence. (b) −90° sequence.

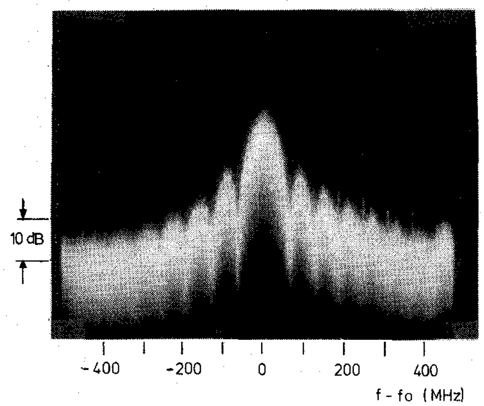
Fig. 7 shows the on and off transitions of the modulator in case of individually switched phase switches. If we define the rise and fall times from 10 to 90 percent of the demodulated output, the rise time of the 90° switch is 1.3 ns and the fall time 1.4 ns. The rise and fall times of the 180° switch are 1.7 ns and 1.5 ns, respectively.

The transitions shown in Fig. 7 were obtained with the driver version (A), which uses microwave transistors. With the driver version (B), using UHF transistors, about 30 percent higher transition times were measured.

Fig. 8 shows the modulator output with the driver version (A) for continuous sequences of +90° and −90° phase shifts at a bit rate of 120 Mbit/s. Since the timing was well adjusted, no undesired phase states occur when



(a)



(b)

Fig. 10. Modulator output spectrum with pseudo-noise input signals. (a) Driver version (A). (b) Driver version (B).

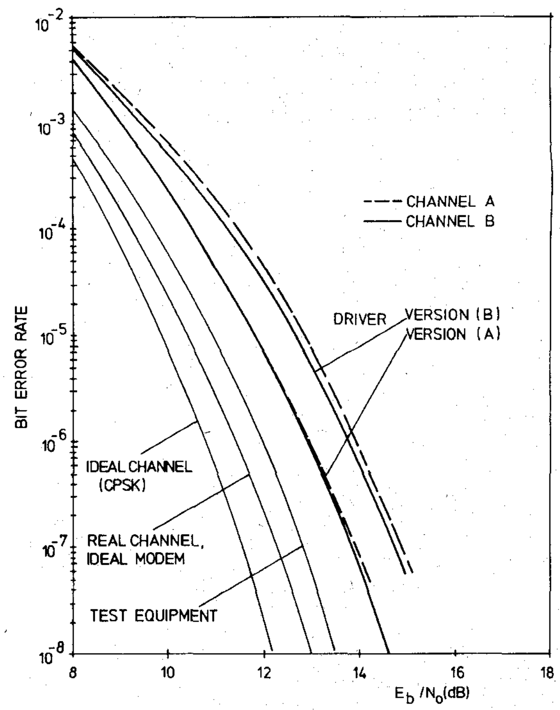


Fig. 11. Bit-error-rate performance of modulator.

both switches act simultaneously. Apart from the small overshoots, phase and amplitude remain constant after the transitions.

Fig. 9 shows the waveforms for $\pm 90°$ sequences with the driver version (B). Due to the long transition times and different switching points in time, undesired phase states occur when both switches act simultaneously. The timing, however, was adjusted to obtain minimum bit-error rates. The effect of these undesired phase states on the bit-error-rate performance is described in the next section.

C. System Performance

The modulator described is part of an experimental regenerative satellite transponder [5], [13] which was built and evaluated. For the system evaluation a special transponder test equipment was used simulating the earth terminal.

In the transponder, the broad modulator output spectrum, shown in Fig. 10, is filtered with a fourth-order Chebyshev bandpass of 67-MHz bandwidth to prevent adjacent channel interference. For simplicity, no pulse shaping is performed in the satellite [10]. After coherent demodulation in the test equipment, the baseband signals are half-shaped (root-Nyquist) with 50-percent cosine roll-off.

Fig. 11 shows the measured bit-error-rate performance of the downlink using the modulator with both driver versions. For comparison, calculated error rates and the error-rate performance of the test equipment, measured over a 14/11-GHz converter, are given, as well. The results for the real channel were obtained by computer simulation assuming ideal modulation and demodulation, but accounting for the measured filter characteristics.

At a bit-error-rate of 10^{-4}, the modulator with the driver version (A) introduces a 0.8-dB higher degradation in the bit energy to noise-density ratio E_b/N_o than the modulator of the test equipment, which is almost ideal. Considering the 0.4-dB degradation by the channel filters, one could contribute at least 0.4-dB degradation to the modulator. Most of this degradation, however, is not caused by modulator impairments but by the power loss with the spectrum truncation, which is not considered in the computer simulations.

The modulator with the driver version (B) causes about 1-dB higher degradation than that with the driver version (A). This is mainly due to the undesired phase states during the transitions. However, the increased power loss on account of the broader spectrum also contributes to the high degradation.

Fig. 10 compares the modulator output spectra with the different driver versions. Due to the timing errors, the spectrum minima are not as deep with version (B) as with version (A). The line components in the spectrum occur if the waveform is trapezoidal instead of rectangular [14]. Therefore, the spectral lines give information about the transition times.

V. Conclusions

The switched-type modulator operating directly at the transmit frequency is most convenient for regenerative satellite repeaters. The simplest and most reliable approach is the serial modulator with circulators and switching diodes. PIN diodes have to be used if a certain power level is requested. Short transition times and exact timing are necessary with the serial modulator. Timing errors and slow transitions result in strongly increased bit-error rates.

Acknowledgment

The authors wish to thank P. Karabanow for the driver development and W. Schreitmüller for the system simulations. Thanks are also due to S. Börner who designed the transponder test equipment.

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Gerhard Ohm was born in Verliehausen, West Germany, on March 5, 1945. He received the Dipl.-Ing. degree in electrical engineering in 1973 and the Dr.-Ing. degree in 1977, both from the Technische Universität Braunschweig, Braunschweig, West Germany.

From 1973 to 1977 he was a Research Assistant at the Institut für Hochfrequenztechnik of the Technische Universität Braunschweig, where he was engaged in investigations on frequency multiplication with MIS diodes. In 1977 he joined AEG-Telefunken, Backnang, West Germany, and worked on FET amplifiers and regenerative satellite repeaters. He is now in charge of the development of satellite home receivers.

Dr. Ohm is a member of VDE/NTG.

Michael Alberty was born in Coesfeld, West Germany, on May 9, 1952. He received the Dip.-Ing. degree in electrical engineering from the Technische Universität Karlsruhe, Karlsruhe, West Germany, in 1976.

He has been with AEG-Telefunken, Backnang, West Germany, since 1976, where he has worked on parametric amplifiers and low-noise FET amplifiers. He is now engaged in the development of components for regenerative satellite repeaters and satellite home receivers.