Ka-Band Direct Digital Receiver

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***Abstract*—A new direct-conversion wide-band (26–28.5 GHz) six-port receiver is proposed for mass-market wireless communications. This six-port receiver is designed to operate without the need for precise power reading and the use of a digital signal processor that is usually required in other receivers. The proposed receiver architecture is chosen to satisfy requirements of hardware receivers used in high-speed QPSK communications. The receiver contains a receiver front-end, QPSK demodulator, and carrier recovery module. A reverse modulation loop was used to provide a rapid carrier recovery. The maximum bit rate is determined solely by the limiting speed of the baseband module. This new hardware receiver is proposed as a robust, rugged, low-cost receiver for use in wide Ka-band wireless mass-market QPSK communications such as local multipoint distribution system services, which is a prime example of communication equipment requiring such receivers. Bit-error-rate results are presented versus the noise and reference signal phase shift.**

***Index Terms*—Carrier recovery, direct conversion, monolithic-microwave integrated-circuit (MMIC) technology, QPSK modulation, six-port junction.**

I. Introduction

DIRECT-CONVERSION receivers offer unique advantages for wireless communications by reducing circuit complexity and allowing a higher level of circuit integration than the traditional heterodyne receivers [1]. Six-port direct-conversion receivers have been proposed [2]–[4] as multimode or software receivers operated with the digital signal processor (DSP) programmed for a number of modulation schemes.

This paper presents recent results obtained on a new six-port-based hardware-type direct digital receiver designed for high-speed QPSK communications. The proposed millimeter-wave approach is also useful in the design of other hardware receivers at lower or higher operating frequencies using either discrete [3] or distributed parameter [2], [4] six-port circuits.

The excellent results obtained with a distributed parameters six-port junction [5]–[7] had a determining role to provide a monolithic-microwave integrated-circuit (MMIC) implementation of this direct digital-receiver architecture.

A carrier recovery module based on a reverse modulation loop (RML) is proposed and demodulation results are obtained in presence of an important Doppler effect. Therefore, this new receiver presents a viable low-cost alternative for mobile terminals.

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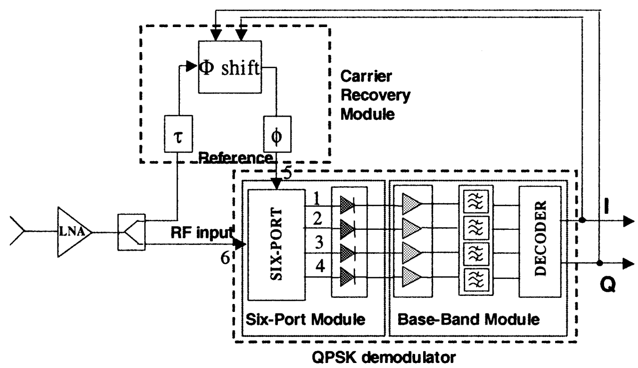

Fig. 1. Ka-band direct digital-receiver architecture.

II. Receiver Architecture and Operating Principle

Fig. 1 shows the hardware receiver architecture composed by a low-noise amplifier (LNA), a QPSK demodulator, and a carrier recovery module. The QPSK demodulator contain two modules, i.e., a six-port module and a baseband module designed to provide output-demodulated signals (I and Q) using the four output signals of the six-port module [5].

The RML [8] provides a rapid carrier recovery from the QPSK modulation at millimeter-wave frequencies. The proposed RML generates the reference signal using a phase shifter controlled by output-demodulated signals and avoids the need of a phase-locked loop (PLL) with a local oscillator (LO). In this design platform, analog signal processing allows very high data rates (up to 60 Mb/s for a bit error rate (BER) less than 10^{-6}) and no DSP is needed for demodulation.

Fig. 2 gives the topology of the six-port module. The six-port junction is specially designed to demodulate a QPSK signal using three 90° hybrid couplers and a Wilkinson power divider. The relative power reading of the output signals gives sufficient information to determine the phase shift between the RF inputs, thereby realizing a QPSK demodulator [5].

III. MHMIC Six-Port Module

The monolithic hybrid microwave integrated circuit (MHMIC) six-port module is fabricated on a 250-μm ceramic substrate with a relative permittivity of 9.9. The MHMIC layout is presented in Fig. 3. The distributed parameter six-port junction, composed of three compact 90° hybrid couplers and a Wilkinson power divider, is placed in the middle of the circuit layout. The surface-mounted RF Schottky diodes and related

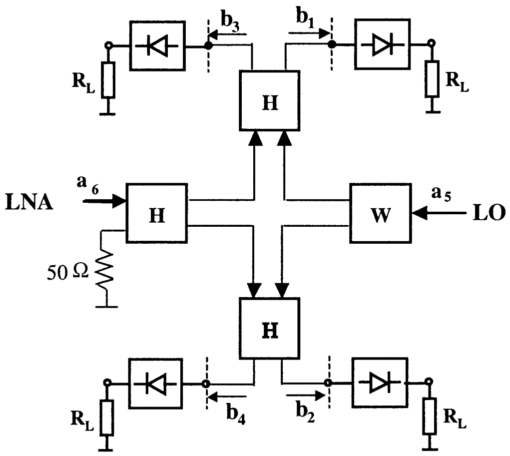

Fig. 2. Block diagram of a six-port module.

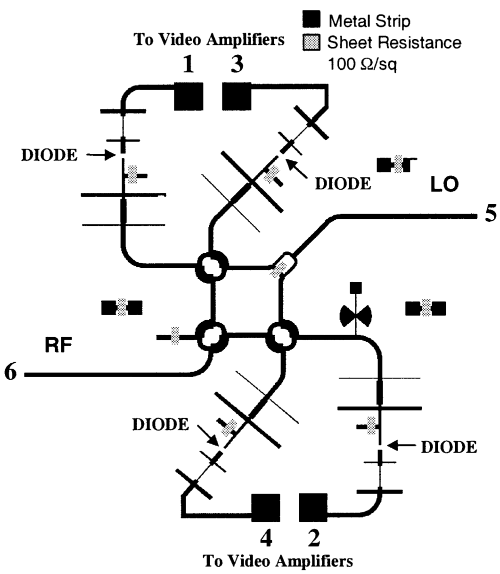

Fig. 3. MHMIC six-port module (size 23 × 23 mm).

wide-band matching circuit networks are connected to the six-port junction's outputs [5].

Fig. 4 shows an excellent match at the RF inputs and an excellent isolation between inputs ($S56$) in the operating frequency band for the MHMIC six-port module. Therefore, the influence of dc offsets in the demodulating process is minimized.

Other simulated and measured S-parameters of this six-port junction were presented in [5]. The measured reflection coefficients S_{11} to S_{66} are less than -24 dB and the isolation between the LNA and LO ports, i.e., S_{56}, is found to be at least -27 dB. The transmission coefficients are close to the theoretical predicted value of -6 dB.

IV. MMIC Six-Port Module

The MMIC six-port module is fabricated on a 100-μm TriQuint Semiconductor GaAs substrate with a relative permittivity of 12.9. We have analyzed three different implementations for the 90° hybrid coupler in the frequency range of 24–30 GHz: with distributed elements, discrete elements, and a combination of both schemes. The distributed element implementation yields a large size (1.39 mm^2), but it has excellent S-parameter performances. The discrete element coupler has a very small size, but the tolerances of its fabrication process over this frequency range lead to poor S-parameter performances. The hybrid implementation using high-impedance transmission lines and capacities leads to very good S-parameter performances.

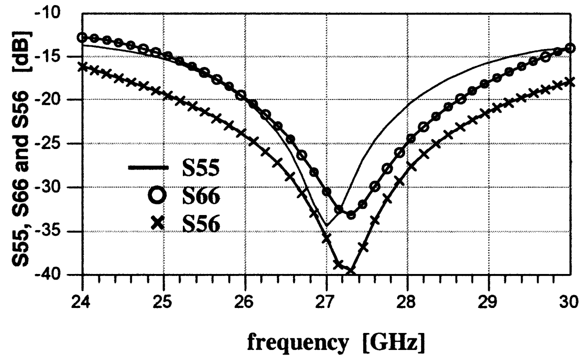

Fig. 4. Return loss and isolation at RF input ports for the MHMIC six-port module.

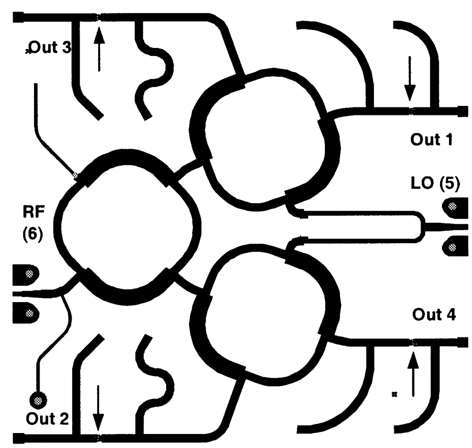

Fig. 5. Distributed parameter MMIC six-port module (size 4 × 4 mm).

Fig. 5 shows the RF topology of a wide-band millimeter-wave MMIC distributed parameter six-port junction with integrated RF Schottky diodes (marked by arrows) and their matching networks using 50-Ω transmission lines. The circuit is realized in a 100-μm GaAs substrate and its size is approximately 4 × 4 mm.

In order to reduce the size of the MMIC circuit, a new approach is proposed. The couplers are realized with high-impedance transmission lines and discrete elements (shunt capacitors of 200-fF value, loaded near the ports of the hybrid couplers). Thus, the diameter of this coupler becomes 600 μm compared with 1330 μm in the first realization. The same Schottky diode is used in the second six-port circuit. The RF Schottky diode matching networks are also realized using the shunt capacitors and high-impedance transmission lines. Fig. 6 shows the RF topology of this new circuit. The size of this circuit is reduced to 2×3 mm, which is approximately 37% of the first six-port's size.

In order to characterize the MMIC six-port junction, a study of its S-parameters was made. The magnitude and phase of the

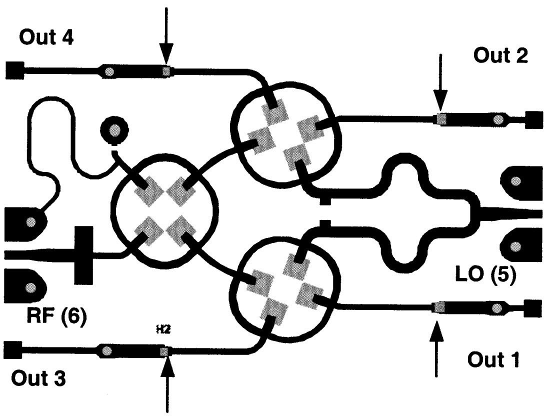

Fig. 6. Hybrid implementation (distributed and discrete elements) of the MMIC six-port module (size 2×3 mm).

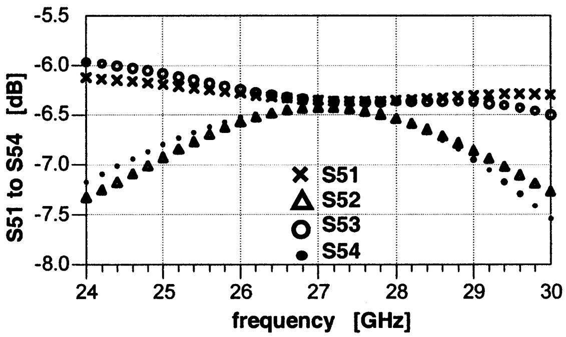

Fig. 7. Magnitude of the transmission S-parameters (LO to outputs).

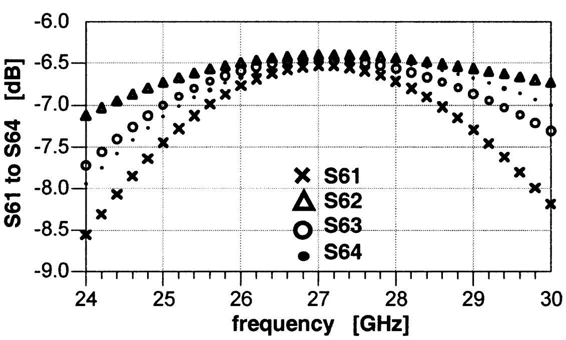

Fig. 8. Magnitude of the transmission S-parameters (RF to outputs).

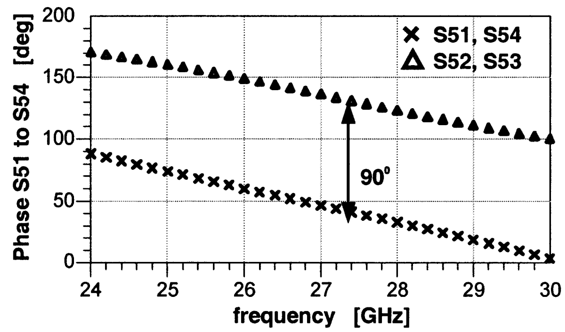

Fig. 9. Phase of the transmission S-parameters (LO to outputs).

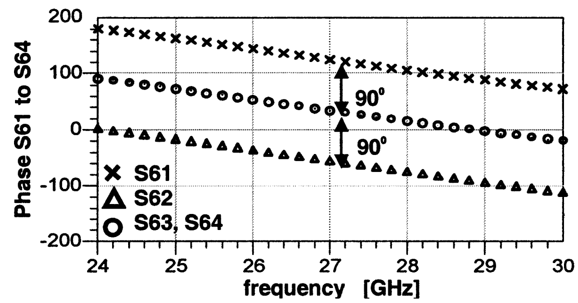

Fig. 10. Phase of the transmission S-parameters (RF to outputs).

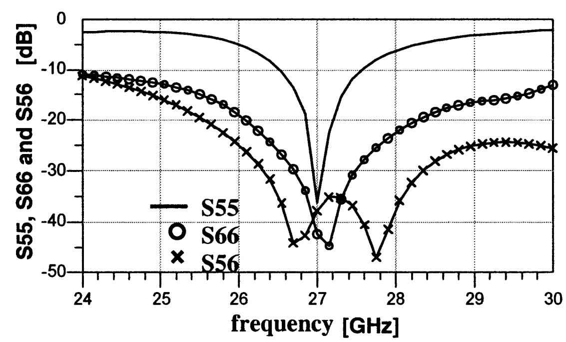

Fig. 11. Return loss and isolation at RF input ports.

S-parameters versus frequency are close to the predicted values. The results of both implementations, given in Figs. 5 and 6, are practically similar. In the operating band, the magnitudes of S-parameters are close to the theoretical predicted values of -6 dB (Figs. 7 and 8) and the phase shifts between the transmission parameters are multiples of 90° over a wide frequency band (6 GHz), as shown in Figs. 9 and 10.

Fig. 11 shows an excellent match at the RF inputs and an excellent isolation between inputs (S_{56}) in the operating frequency band for the MMIC six-port module (including the Schottky diodes). Therefore, one can draw the same conclusion as for the MHMIC circuit, i.e., the influence of dc offsets in the demodulating process is minimized.

The RF design of the six-port junction is such that only one of four possible modulation states is correctly identified, at any given time, by an analogue decoder (baseband module). Harmonic-balance simulation of the MMIC six-port module is shown in Fig. 12. The LO and RF input power levels are both set at -3 dBm. Waveforms displayed in Fig. 12 indicate that each output voltage of the six-port junction has a single maximum value over a 360° phase shift between the RF input and LO signal. This means that $V_{\rm out3}, V_{\rm out4}, V_{\rm out1}, V_{\rm out2}$ have a maximum value for 0°, 90°, 180°, and 270° phase shift, respectively, between the input and LO signals.

V. Baseband Module

The baseband module (see Fig. 1), composed of video amplifiers, low-pass filters, and an I and Q decoder, provides the output-demodulated signal.

Fig. 13 shows the block diagram of the I and Q decoder composed of high-speed comparators and a 4–2-bit encoder. The four input voltages are $A * V_{\rm out}$, where A is the gain of video amplifiers. To obtain an extended dynamic range for the receiver, the decoder uses a relative comparison between $V_{\rm out}$ signals [5]. A dynamic threshold (e.g., proportional with the average value of $V_{\rm out}$) is more suitable in the case of the MMIC six-port

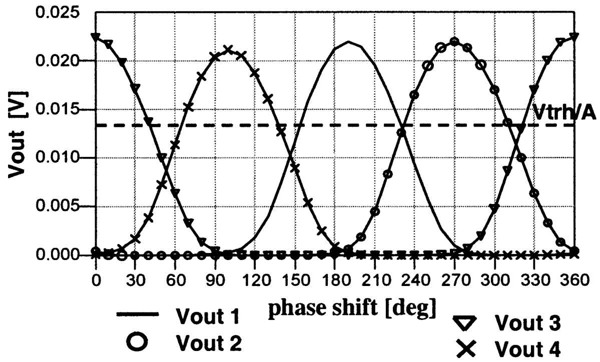

Fig. 12. Output voltages of the MMIC six-port module versus the phase shift of the input signals.

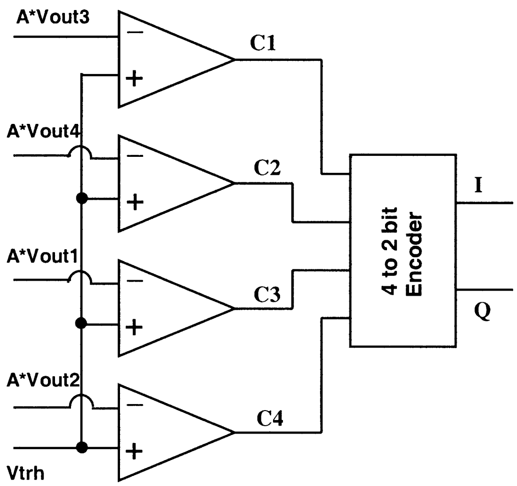

Fig. 13. Block diagram of an I and Q decoder.

TABLE I
ENCODER LOGICAL TABLE

C1	C2	C3	C4	I	Q
0	1	1	1	1	1
1	0	1	1	0	1
1	1	0	1	0	0
1	1	1	0	1	0

versions, where the maximum value of each V_{out} is very well marked versus the phase shift, but the minimum value is flat (Fig. 12). Therefore, if the RF signal level changes, the magnitude of V_{out} signals also changes and the dynamic threshold "updates" its value.

Table I shows the output I and Q bit values of the encoder. The output demodulated signals versus the phase shift between RF input and LO signals, as shown in Fig. 14, confirm the operating principle of the receiver. The four states of the output signals $(11, 01, 00, 10)$ are obtained during a 360° phase shift of input signal.

VI. CARRIER RECOVERY MODULE

The carrier recovery module uses the input QPSK and the demodulated signals to provides the reference signal for the QPSK demodulator.

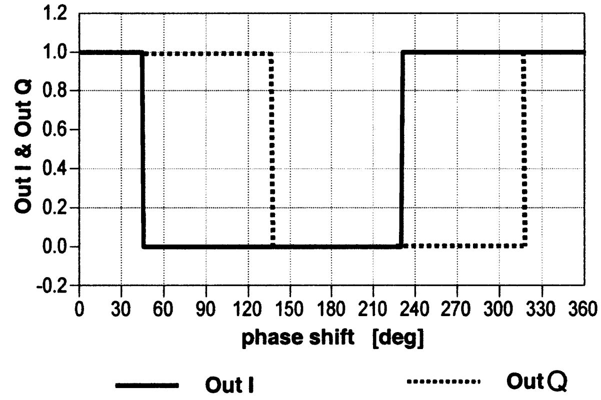

Fig. 14. I and Q output signals of the baseband module versus the phase shift of the input signals.

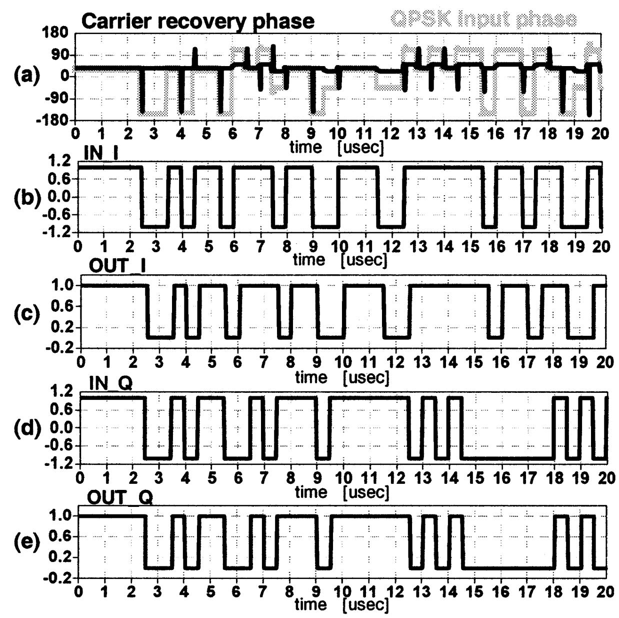

Fig. 15. (a) RF input phases. (b)–(e) Related I and Q waveforms.

In a QPSK modulated signal, four possible states of the input signal phase are possible [e.g., $\pm 45°$ and $\pm 135°$ for the QPSK input phase represented in Fig. 15(a)]. In the RML process, a controlled phase shifter was used to obtain the carrier recovery signal (see Fig. 1). A 90° multiple phase shift was added to the QPSK input signal to cancel the original modulation. A time delay (in our case, $t = 0.1$ μs) was used to compensate the signal delay via the QPSK demodulator. A second phase shifter, i.e., Φ in Fig. 1, is capable of adjusting the appropriate reference phase for the carrier recovery signal [45° in Fig. 15(a)].

Fig. 16 shows the simulated results of the recovered carrier spectrum. It is seen that the signal level of the carrier is 30 dB above other spectral lines.

The reference signal level follows the input carrier level because a RML technique was used. Therefore, the dynamic range of the receiver increases, compared to the case of a fixed reference signal level, where a 40-dB dynamic range was measured [5].

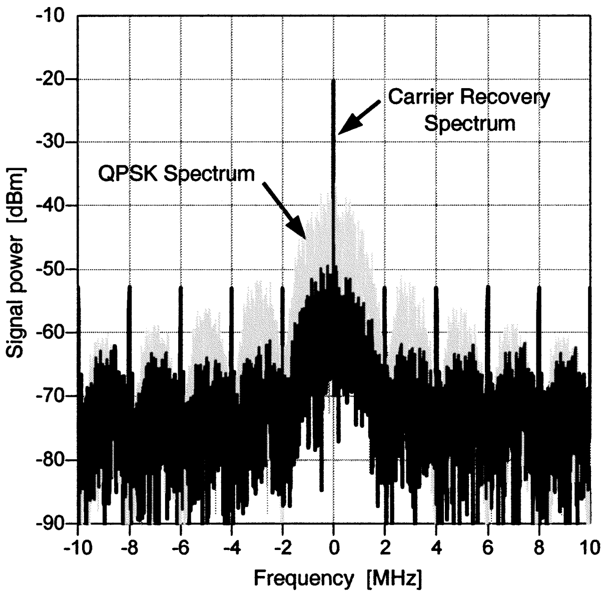

Fig. 16. QPSK and carrier recovery simulated spectrum at 27 GHz and 4-Mb/s bit rate.

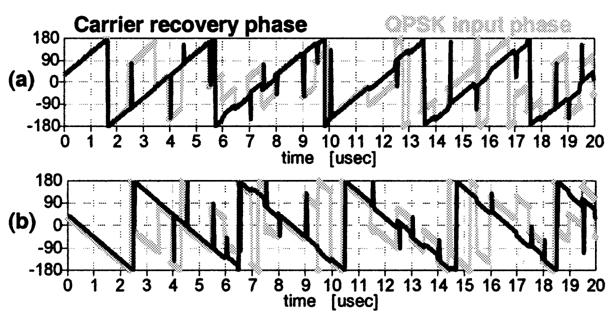

Fig. 17. Phases of carrier recovery signal and QPSK modulated signal with ±250-kHz Doppler frequency shift on carrier at 4 Mb/s.

In conclusion, using the RML technique and a dynamic threshold to compare the V_{out}, a very large dynamic range (over 60 dB) was obtained for a BER less than 10^{-6}.

VII. Demodulation Results

Simulations were performed, with an ideal model of the controlled phase shifter and our tested model [5] of the QPSK demodulator, using Advanced Design Software (ADS) of Agilent Technologies, Palo Alto, CA. Results given in Figs. 15 and 17 support the new receiver architecture with RML.

Fig. 15(a) shows the simulated phase of the pseudorandom QPSK modulated signal and the phase of its carrier-recovered signal. It is seen that "glitches" occur in the phase of recovered carrier each time the phase state of the carrier signal is changed. However, Fig. 15(b)–(e) shows that the receiver is insensitive to "glitches." Simulation results given in Figs. 15(b)–(e) also illustrates accuracy of recovered data for a pseudorandom bit sequence.

Fig. 17 shows the phases of the carrier recovery and QPSK modulated signals with ±250-kHz Doppler frequency shift on a carrier at a 4-Mb/s bit rate (corresponding to a relative speed up to 10 000 km/h for a 27-GHz carrier). It is seen that the carrier recovery signal follows the carrier of the QPSK modulated

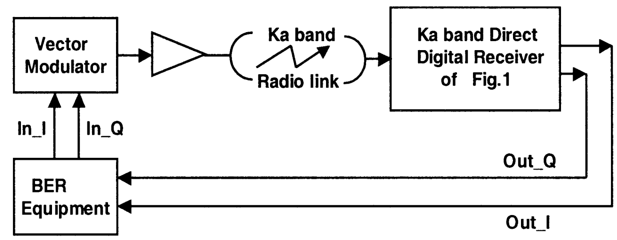

Fig. 18. Block diagram of BER simulation test bench.

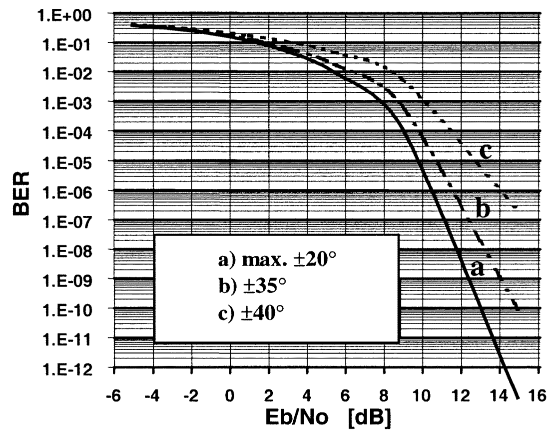

Fig. 19. Measured BER for the phase errors from synchronism at 27 GHz.

signal in spite of the ± Doppler frequency shift. Therefore, the mobile applications at high bit rates of this new receiver are very promising.

Fig. 18 shows the block diagram of a BER simulation test bench. A pseudorandom bit sequence ($\mathrm{In}\,I$ and $\mathrm{In}\,Q$) is generated using BER transmitter equipment, and a QPSK modulated signal is obtained with a vector modulator. The propagation path is simulated and the input RF modulated signal is processed in the proposed Ka–band direct digital receiver. The input and output waveforms were presented in Figs. 15 and 17. The BER receiver equipment evaluates the $\mathrm{Out}\,I$ and $\mathrm{Out}\,Q$ signals and counts the errors. The measurement test bench was presented in [5] and was used with a coherent carrier at 27 GHz. A controlled phase shifter is presently in design to complete the carrier recovery module. For BER measurements with a coherent carrier, the LO power was set to -20 dBm. For BER simulations, the same power level of the carrier recovery signal was obtained (see RML simulations in Fig. 16) and used in the demodulating process. For BER measurements and simulations, the bit rate was set at 20 Mb/s.

Fig. 19 shows the measured BER with a coherent carrier, versus phase error from synchronism (MHMIC design), and it is seen that, for a shift error less than 20°, the BER curve is identical with the theoretical one for the QPSK modulation [see Fig. 19(a)]. If the phase error rises, the BER rises rapidly, as seen in Fig. 19(b) and (c).

Fig. 20 shows the BER simulations obtained with a MMIC six-port using an RML carrier recovery circuit over the operating band (26–28.5 GHz) and the results on measurements obtained with a MHMIC six-port using a coherent carrier at 27 GHz. The simulated BER curve is identical with the

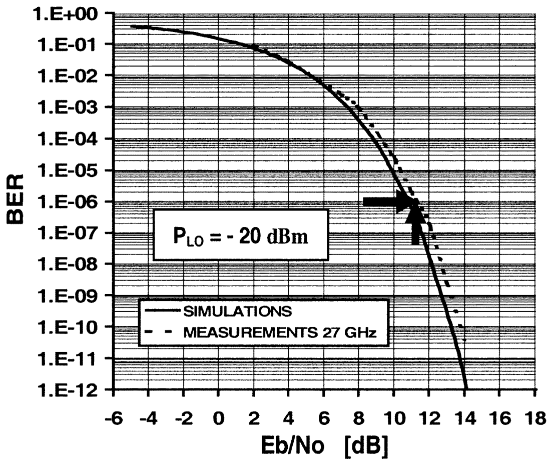

Fig. 20. BER simulation and measurement results versus Eb/No over the operating band.

theoretical one, as expected, because important phase errors can be tolerated with a QPSK six-port demodulator (see Fig. 19).

In the presence of a Doppler effect, as seen in Fig. 17, the same simulated BER results were obtained for a bit rate up to 4 Mb/s. The bit rate can be increased (at least 60 Mb/s) for a Doppler frequency shift on a carrier less than 10 kHz (corresponding to a relative speed up to 400 km/h for a 27-GHz carrier). The bit error occurs when the carrier phase shift exceed 45° during a bit length, therefore, the maximum bit rate is related to relative speed for mobile applications.

Both simulated and experimental results indicate a wide-band capacity for such receivers and confirm a very good agreement between simulations and measurements.

VIII. Conclusion

A new direct-conversion hardware receiver based on six-port technology has been presented. The six-port circuit of this receiver was integrated in MHMIC technology in our own laboratory and in 0.25-μm GaAs pseudomorphic high electron-mobility transistor (pHEMT) technology at TriQuint Semiconductor, Richardson, TX.

The BER results are comparable to a standard direct-conversion receiver [9] and the proposed concept is verified by measurements and simulations based on an integrated circuit prototype. The simulations obtained with an analog carrier recovery module based on the RML technique were also presented. New results on the RML technique, obtained in our laboratory, have been published [10].

This new direct digital receiver presents a viable alternative for mobile terminals. It is shown that the new circuit can effectively operate with a low LO power (-20 dBm) in the presence of an important Doppler effect.

The new direct-conversion receiver could be used in many space and terrestrial applications such as: 1) broad-band satellite communication; 2) point-to-point communications; 3) LMDS; and 4) terminals for multimedia and the Internet, etc. This approach can also be used to obtain a low-cost hardware millimeter-wave receiver designed for QPSK modulation in a high-speed satellite Internet.

Acknowledgment

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Dr. Brehm was chairman of the 1989 IEEE GaAs Integrated Circuit Symposium and Technical Program chairman for the 1999 Emerging Technology Symposium on Broad-Band Wireless Internet Access. He continues to be active in the IEEE. From 1998 to 2000, he was a Distinguished Microwave Lecturer for the IEEE Microwave Theory and Techniques Society (IEEE MTT-S).

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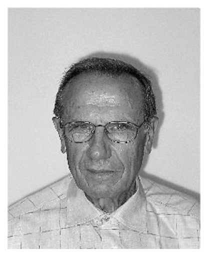
He conducted research in the Laboratoire d'Electromagnetisme, Microondes et Optoelectronics (LEMO), Grenoble, France, prior to joining the Department of Electrical and Computer Engineering, University of Victoria, Victoria, BC, Canada. He subsequently joined the Department of Electrical and Computer Engineering, Ecole Polytechnique de Montréal (Faculty of Engineering, University of Montréal) as an Assistant Professor, and is currently a Full Professor and Tier-I Canada Research Chair in Radio-Frequency and Millimeter-Wave Engineering. He has been a Visiting or Guest Professor at Telecom-Paris, Paris, France, and INP-Grenoble, Grenoble, France, the City University of Hong Kong, the Swiss Federal Institute of Technology (ETH-Zurich), Zurich, Switzerland, the National University of Singapore, Singapore, the University of Ulm, Ulm, Germany, as well as many short-term visiting professorships with other universities. He also holds an honorary visiting professorship at the Southeast University, Nanjing, China, and an honorary professorship at the Nanjing University of Science and Technology, Nanjing, China. He has been the Head of the FCAR Research Group of Quebec on RF and microwave electronics, the Director of the Poly-Grames Research Center, as well as the Founding Director of the newly developed Canadian Facility for Advanced Millimeter-Wave Engineering (FAME). He has authored or coauthored over 320 referred papers, and also several book chapters. His current research interests involve hybrid/monolithic planar and nonplanar integration techniques, active and passive circuits, antenna arrays, advanced field-theory-based computer-aided design (CAD) and modeling techniques, and development of low-cost RF and millimeter-wave transceivers. He is also interested in the modeling and design of microwave photonic circuits and systems. He serves on the Editorial Board of *Microwave and Optical Technology Letters*.

Dr. Wu is a member of the Electromagnetics Academy. He has held many positions in and has served on various international committees, including the vice chairperson of the Technical Program Committee (TPC) for the 1997 Asia–Pacific Microwave Conference, the general co-chair of the 1999 and 2000 SPIE International Symposium on Terahertz and Gigahertz Electronics and Photonics, and the general chair of 8th International Microwave and Optical Technology (ISMOT'2001). He has served on the Editorial or Review Boards of various technical journals, including the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, and the IEEE MICROWAVE AND GUIDED WAVE LETTERS. He served on the 1996 IEEE Admission and Advancement (A&A) Committee, the Steering Committee for the 1997 joint IEEE Antennas and Propagation Society (IEEE AP-S)/URSI International Symposium. He has also served as a TPC member for the IEEE Microwave Theory and Techniques Society (IEEE MTT-S) International Microwave Symposium. He was elected into the Board of Directors of the Canadian Institute for Telecommunication Research (CITR). He served on the Technical Advisory Board of Lumenon Lightwave Technology Inc. He is currently the chair of the joint IEEE chapters of MTT-S/AP-S/LEOS in Montréal, QC, Canada. He was the recipient of a URSI Young Scientist Award, the Institute of Electrical Engineers (IEE), U.K., Oliver Lodge Premium Award, the Asia–Pacific Microwave Prize Award, the University Research Award "Prix Poly 1873 pour l'Excellence en Recherche" presented by the Ecole Polytechnique de Montréal on the occasion of its 125th anniversary, and the Urgel-Archambault Prize (the highest honor) in the field of physical sciences, mathematics, and engineering from the French–Canadian Association for the Advancement of Science (ACFAS). In 2002, he was the first recipient of the IEEE MTT-S Outstanding Young Engineer Award. He was inducted as a Fellow of the Canadian Academy of Engineering (CAE) in 2002.



Renato G. Bosisio (M'79–SM'89–F'95) was born on June 28, 1930, in Monza, Italy. He received the B.Sc. degree in mathematics and physics from McGill University, Montréal, QC, Canada, in 1951, and the M.A.Sc. degree in electrical engineering from the University of Florida, Gainesville, in 1963.

From 1951 to 1953, he was a Research Scientist with the Defense Research Telecommunications Establishment (Electronics Laboratory), Ottawa, ON, Canada. From 1953 to 1959, he was with the Canadian Marconi Company, Montréal, QC, Canada, and also with the English Electric Valve Company, Chelmsford, U.K., where he was involved with microwave magnetrons. From 1959 to 1964, he was with the Sperry Electron Tube Division, Gainesville, FL, where he performed research and development work on microwave-crossed field devices. From 1964 to 1965, he was with the Varian Associates of Canada, Georgetown, ON, Canada, where he was engaged in the development of traveling wave tubes. He then joined the faculty at the University of Montréal, Montréal, QC, Canada, where he became an Associate Professor in electrical engineering with the École Polytechnique de Montréal in 1965, Professor and Head of the Electromagnetic and Microwave Group in 1971, Head and founder of the Advanced Microwave Research Group (Poly-Grames) in 1990, and Emeritus Professor in 1995. In 1994, he founded and headed the Poly-Grames Research Centre for graduate student research in the design, fabrication, and measurement of microwave/millimeter-wave devices, components, and subassemblies destined for use in advanced radar and communication systems. He has authored or coauthored 180 journal publications, 220 refereed conference presentations, numerous technical reports, and industrial consultations in microwaves and millimeter waves. He has also been involved in numerous microwave innovations and holds 12 patents. His research interest cover a wide area in microwave/millimeter-wave related to advanced wireless LANs, satellite/satellite/earth communication links, and point-to-point communications and automotive guidance systems. His research topics include automated and computer-aided microwave/millimeter-wave instrumentation and measurements, characterization of dielectric materials and electron devices, high-power microwave power applications, design/fabrication/test of microwave/millimeter-wave monolithic and hybrid integrated circuits, and the development of new microwave/millimeter-wave six-port technology for direct digital receivers, radar, and intelligent integrated sensors.

Prof. Bosisio is a member of the Sigma Xi Research Society at McGill University (1982), Phi Kappa Phi Learned Society at the University of Florida (1963) and l'Ordre des Ingénieurs du Québec (1965). He has been the recipient of a number of awards including the IEEE Canada Outstanding Educator Award (1996), the École Polytechnique Outstanding Professor Award (1973), and The Inventor Award presented by Canada Patents and Development Limited (1971).