High-Speed ASK Transceiver Based on the NRD-Guide Technology at 60-GHz Band

Futoshi Kuroki, *Member, IEEE,* Masayuki Sugioka, Shinji Matsukawa, Kengo Ikeda, and T. Yoneyama, *Fellow, IEEE*

***Abstract*— A new type of high-speed amplitude shift-keying (ASK) transceiver has been developed in an integrated manner at 60 GHz by using the nonradiative dielectric waveguide (NRD-guide) technology. An emphasis is placed on the high-speed performance of the newly developed ASK modulator. The modulator uses a Schottky barrier diode (SBD), which has higher switching speed than a p-i-n diode. In addition, the operation principle of it is different from that of the conventional p-i-n diode modulator. A pair of NRD-guide transceivers have been fabricated and 400-Mb/s data-transmission test has been carried out successfully by using them.**

***Index Terms*— Amplitude shift-keying modulator, millimeter-wave integrated circuits, millimeter-wave transceivers, nonradiative dielectric waveguide, wireless LAN.**

I. Introduction

WITH the opening of the broad-band integrated services digital network (ISDN) era, asynchronous transfer mode (ATM) based communication systems with bit rates ranging from 156 Mb/s to 2.5 Gb/ps are being built in optical-fiber networks [2]. Millimeter waves have also attracted much attention for the construction of wireless communication systems having such high bit rates. Actually, various millimeter-wave front ends for local area network (LAN) use have been developed by using printed transmission lines such as microstrip lines and coplanar waveguides [3], [4]. These printed transmission lines are preferable for applications at microwave frequencies, but they suffer from a lot of transmission losses at millimeter-wave frequencies [5]. Another candidate as a transmission medium for millimeter-wave integrated circuits [6] is the NRD-guide, which consists of rectangular dielectric strips inserted in a below cutoff parallel metal-plate waveguide and features no radiation at curved sections and discontinuities as well as small transmission loss inherent to dielectric waveguides. Indeed, NRD-guide has been used to build amplitude shift-keying (ASK) transceivers at 60 GHz, in which ASK modulators with a GaAs p-i-n diode are incorporated to achieve 100-Mb/s data-transmission rate [7]. From a view point of high-speed operation of the modulator, a Schottky barrier diode (SBD) is more attractive than a p-i-n diode because reverse recovery time of the former is smaller than that of the latter [7].

Having this fact in mind, we propose a new type of NRD-guide ASK modulator in this paper, whose operation principle is different from that of the p-i-n diode counterpart. By integrating the newly developed modulator together with other key devices, an NRD-guide ASK transceiver having the improved high-speed performance as well as the compact size comparable with that of a name card has been fabricated at 60 GHz. A high-speed data-transmission test has been successfully performed at a bit rate beyond 400 Mb/s.

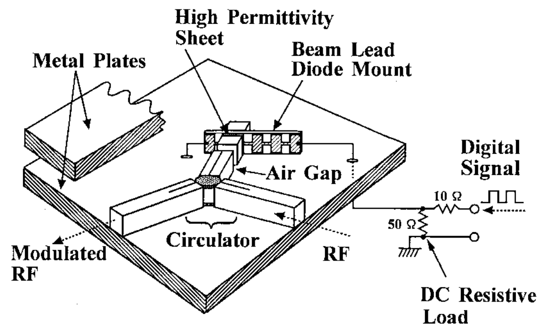


Fig. 1. Structure of NRD-guide ASK modulator using SBD.

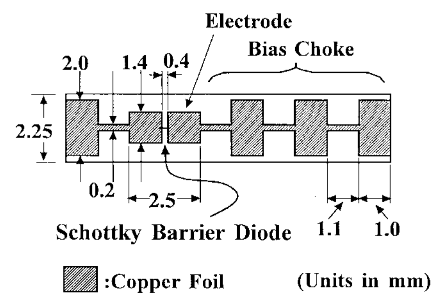


Fig. 2. Structure of NRD-guide beam-lead diode mount at 60-GHz band.

II. New Type of NRD-Guide ASK Modulator

A. Operation Principle

The structure of the newly developed NRD-guide ASK modulator with a built-in circulator [6] is shown in Fig. 1. The beam-lead type of the SBD is bonded across a slot between two electrodes etched on a dielectric substrate together with $\lambda/4$ RF choke structures, as shown in Fig. 2. The diode

Manuscript received October 15, 1997; revised March 4, 1998.

F. Kuroki, M. Sugioka, and S. Matsukawa are with the Department of Electrical Engineering, Kure National College of Technology, Kure 737, Hiroshima, Japan (e-mail: kuroki@kure-nct.ac.jp).

K. Ikeda is with the Communication Systems Development Laboratories, Sharp Corporation, Hiroshima 739-01, Japan.

T. Yoneyama is with the Research Institute of Electrical Communication, Tohoku University, Sendai 980-11, Japan.

Publisher Item Identifier S 0018-9480(98)04044-7.

0018–9480/98$10.00 © 1998 IEEE

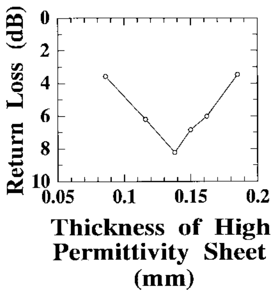


Fig. 3. Measured return-loss characteristics of ASK modulator with forward-biased SBD versus thickness of high-permittivity sheet.

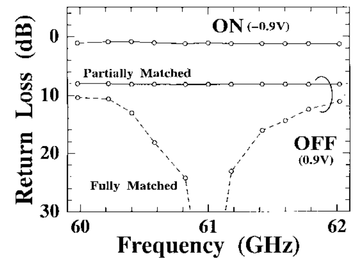


Fig. 4. Measured return-loss characteristics of ASK modulator with forward-biased and reverse-biased SBD versus frequency.

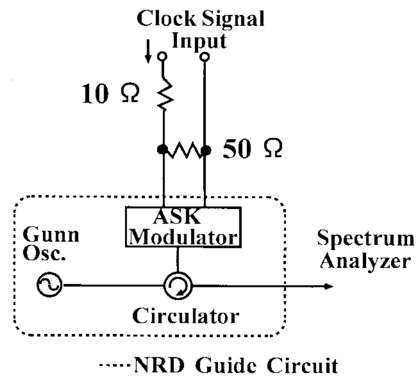


Fig. 5. Block diagram of NRD-guide ASK transmitter.

mount is placed at one port of the NRD-guide circulator. A high-permittivity sheet and an air gap are installed at proper positions to make matching between the NRD-guide and SBD when it is forward biased [8]. Incident millimeter waves are, therefore, absorbed by a dc resistive load connected to the SBD under the forward-biased condition, whereas those are reflected back under the zero or reverse-biased condition. Thus, pulse modulated millimeter waves appear at the output port of the circulator. This ASK modulator can be expected to operate with higher speed than the p-i-n diode-type modulator because the minority carrier lifetime of the SBD is picosecond order while that of the p-i-n diode is nanosecond order. Another advantage of this modulator is that the matched load used to create the OFF state is a simple dc resistive load and, hence, a considerable size reduction.

B. Design

The metal plate separation of NRD-guide is determined to be 2.25 mm so as to be less than half a free-space wavelength at 60 GHz. Teflon with a relative permittivity of 2.04 is chosen as the material of the dielectric strip because of its low-loss characteristics at millimeter wavelengths and chemical stability. The dielectric strip is 2.25 mm in height and 2.5 mm in width. This cross-sectional dimensions guarantee the single-mode operation over the frequency range from 55 to 65.5 GHz.

A detailed view of the beam-lead diode mount, which is created on a glassfiber-woven Teflon substrate with relative permittivity of 2.6, is shown in Fig. 2. The slot between electrodes is 1.4 mm in length and 0.4 mm in width and the two electrodes including the slot are 2.5 mm in total width, being identical to the width of the dielectric strip itself. The RF choke is 0.2 mm in narrow width and 2.0 mm in wide width, and is 0.9 mm in length so as to be a quarter-wavelength on the substrate.

At first, the diode mount was placed at the truncated end of the dielectric strip together with the high-permittivity sheet, and the return loss was measured against thickness of the sheet with bias voltage of 0.9 V for the diode, as shown in Fig. 3. The result indicates that the optimum thickness of the sheet for the maximum return loss is 0.14 mm. Measured return losses of the diode with forward and reverse bias voltages of ±0.9 V, respectively, are shown in Fig. 4 as a function of frequency by solid curves. The insertion loss less than 1.5 dB in the ON state and a flat ON/OFF ratio of 7 dB have been obtained. In order to improve the ON/OFF ratio at the operation frequency of 61 GHz, the air gap with a known impedance calculated by the finite-element method [9] was introduced at a proper position which was determined by measuring the diode impedance including the high-permittivity sheet based on standing-wave patterns along the dielectric strip [10]. The return-loss characteristics of the gap-matched ASK modulator were measured, as shown in Fig. 4, by dotted curves. The ON/OFF ratio of more than 30 dB at 61 GHz has been achieved, while the insertion loss of the ON state has been still less than the predicted 1.5 dB.

C. Performance for 400-Mb/s Clock Signal

An NRD-guide ASK transmitter including the Gunn oscillator, circulator, and ASK modulator has been assembled, as shown in Fig. 5. The Gunn oscillator, whose oscillation frequency is stabilized at 60.960 GHz by means of a high-Q ceramic resonator, produces oscillation power of 30 mW, and the circulator has an insertion loss less than 0.5- and 20-dB isolation bandwidth of 3 GHz.

A 200-MHz clock signal with duty factor of 50% was used as a modulating signal, which is equivalent to a 400 Mb/s nonreturn-to-zero (NRZ) pulse train. Fig. 6 shows the spectrum of the millimeter-wave carrier modulated with such a pulse train by using the fabricated modulator. As is well known, the frequency spectrum of the clock signal with duty factor of 50% consists of only odd harmonic sidebands. The spectrum in Fig. 6 confirms this statement and, hence, a satisfactory operation of the modulator.

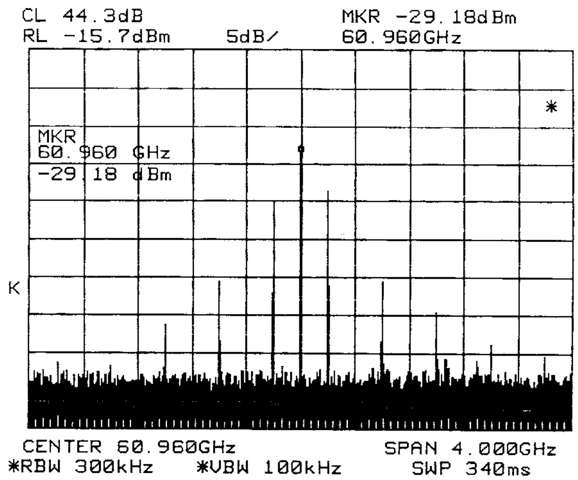
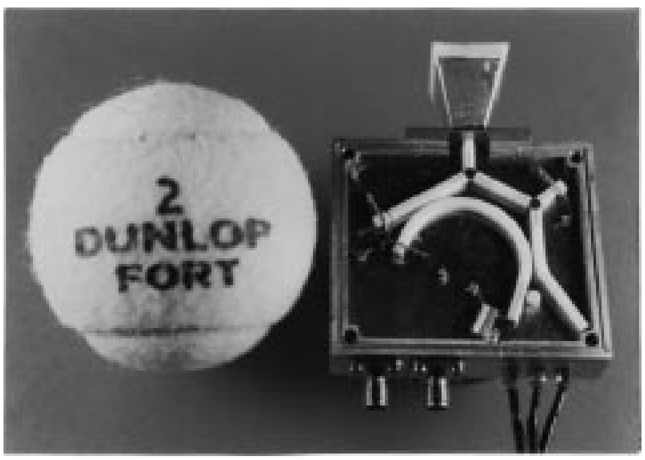
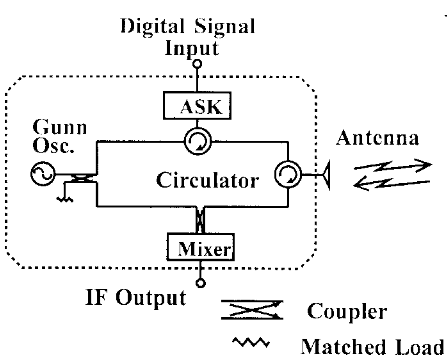


Fig. 6. Spectrum of millimeter-wave carrier modulated with 400-Mb/s pulse train.



(a)



(b)

Fig. 7. NRD-guide ASK transceiver. (a) Photograph. (b) Block diagram.

III. NRD-Guide ASK Transceivers and High-Speed Data-Transmission Test

A. Performance of NRD-Guide ASK Transceivers

A pair of NRD-guide ASK transceivers tuned at 59.785 and 60.960 GHz have been fabricated for a data-transmission test. The photograph and block diagram of it are shown in Fig. 7.

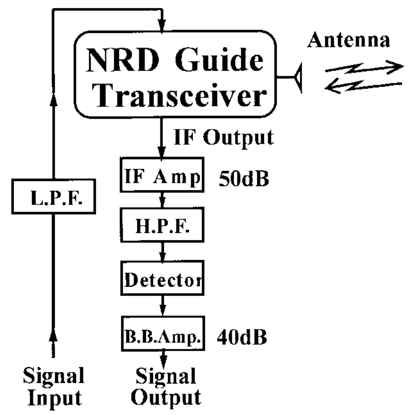


Fig. 8. System configuration of wireless data-transmission test.

TABLE I
PERFORMANCE OF NRD-GUIDE ASK TRANSCEIVER

Frequency	(GHz)	60.960	59.785
Output Power	(mW)	11.6	11.0
Modulation		ASK	
Bit Rate	(Mbps)	400	
Intermediate Frequency	(MHz)	1175	
Conversion Loss	(dB)	9	
Antenna Gain	(dBi)	20	
Size (Excluding Antenna)	(mm)	64×56	

It consists of an ASK modulator as described above, GaAs SBD balanced mixer, frequency-stabilized Gunn oscillator, circulators, and directional couplers. Output power of the Gunn oscillator is divided into two parts: the carrier and local oscillation (LO) power by using a directional coupler. The coupler is adjusted so as to supply the LO power of 10 mW, which is required for the minimum conversion loss of the mixer. As a result, the power of carrier is reduced to 20 mW.

Since a circulator is implemented as a duplexer, a single pyramidal horn antenna is enough for both transmission and reception. The antenna is covered with a thin Teflon sheet over the 16 mm $\times$ 23 mm aperture and fed by a tapered dielectric rod of 3 mm in length. Its measured gain is 20 dBi. All circuit components are contained in a compact housing of 64 mm $\times$ 56 mm in area. Performances of the transceivers are summarized in Table I.

B. High-Speed Data-Transmission Test

A system configuration for a wireless data-transmission test is shown in Fig. 8. In order to avoid interferences between transmitted and received waves caused in a single antenna, high- and low-pass filters are indispensable at the IF output terminal and the input terminal for baseband signals. In this way, duplexing data transmission between two transceivers can be carried out.

At first, the bit error rate (BER) for a pseudo-random binary signal (PRBS) having the bit rate of 400 Mb/s and the length of $2^{11} - 1$ was measured against received power, as shown in Fig. 9, where two transceivers were connected through a

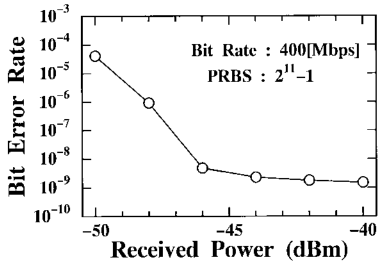


Fig. 9. Measured BER versus received power.

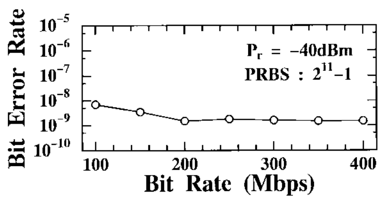


Fig. 10. Measured BER versus bit rate.

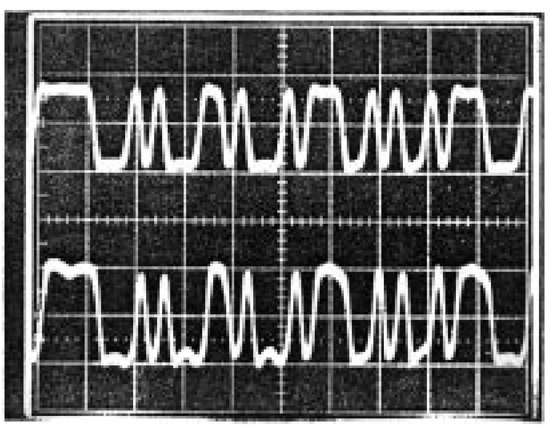


Fig. 11. Comparison between modulating (top) and demodulated (bottom) waveforms with 400-Mb/s pseudorandom signal (vertical axis: 0.5 V/div; horizontal axis: 10 ns/div).

waveguide with a variable attenuator. As the received power becomes higher than −46 dBm, the BER becomes smaller than 10^{-8}.

Fig. 10 shows the BER measured by fixing the received power at −40 dBm as a function of modulation bit rate. Since the BER is 2×10^{-9} on average over the bit rates from 100 to 400 Mb/s, it is expected that the NRD-guide transceivers have the capability of high-speed operation beyond 400 Mb/s. Unfortunately experiments beyond 400 Mb/s is limited by the capability of the instruments at hand.

Toward the application of indoor wireless communications, the high-speed data-transmission test has been performed by locating two transceivers separately by the distance of 5 m in a narrow hall. The observed modulating (top) and demodulated (bottom) waveforms of PRBS with bit rate of 400 Mb/s is shown in Fig. 11. The two patterns are identical in shape, thus, it is confirmed that the transmitted signal can be clearly recovered in the receiver.

IV. Conclusion

A new type of NRD-guide ASK modulator has been developed. It has a great advantage of high-speed operation in excess of 400 Mb/s since SBD having small reverse-recovery time is used instead of conventional p-i-n diodes. The modulator is not only excellent in high-speed performance, but also small in size because it does not need a bulky attenuator. Compact ASK transceivers possessing a bit rate beyond 400 Mb/s have been fabricated by assembling the ASK modulator, frequency-stabilized Gunn oscillator, circulators, directional couplers, and balanced mixer. Since 400-Mb/s data-transmission test has been successful, the transceivers can be applied to wireless portions in ATM networks. The issue to be considered next is multipoint millimeter-wave communication systems. The NRD-guide technology is expected to play a key role in such applications.

References

[1] P. E. Geen, Jr., “Optical networking update,” *IEEE J. Select. Areas Commun.*, vol. 14, pp. 764–779, June 1996.

[2] H. H. Meinel, “Millimeter-wave technology advances since 1985 and future trends,” *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 759–767, May 1991.

[3] K. Ohata *et al.*, “60-GHz-band ultra-miniature monolithic T/R modules for multimedia wireless communication systems,” *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 2354–2360, Dec. 1996.

[4] T. Itoh and J. Rivera, “A comparative study of millimeter-wave transmission lines,” *Infrared Millimeter Waves*, vol. 9, ch. 2, pp. 95–132, 1983.

[5] T. Yoneyama, “Millimeter wave integrated circuits using nonradiative dielectric waveguide,” *IEICE Trans.*, vol. J73-C-I, no. 3, pp. 87–94, Mar. 1990.

[6] F. Kuroki and T. Yoneyama, “NRD guide digital transceivers for millimeter wave LAN system,” *IEICE Trans.*, vol. 79-E, no. 12, pp. 1759–1763, Dec. 1996.

[7] M. Uenohara, “Microwave semiconductor device,” Corona Co. Ltd., Tokyo, Japan, 1971.

[8] ——, “Nonradiative dielectric waveguide circuit components using beam-lead diodes,” *IEICE Trans.*, vol. J73-C-I, no. 2, pp. 71–76, Feb. 1989.

[9] Y. Endo and T. Yoneyama, “Finite element analysis of discontinuities in nonradiative dielectric waveguide,” *IEICE Trans.*, vol. J72-C-I, no. 1, pp. 59–67, Jan. 1989.

[10] T. Yoneyama, N. Tozawa, and S. Nishida, “Loss measurements of nonradiative dielectric waveguide,” *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 943–946, May 1991.

Futoshi Kuroki (M’88) received the B.E. degree in electronics engineering from Kyushu Institute of Technology, Japan, in 1982, and the M.E. and Ph.D. degrees in electrical communication engineering from Tohoku University, Sendai, Japan, in 1984 and 1987, respectively.

From 1987 to 1995, he was a Research Associate at the Research Institute of Electrical Communication, Tohoku University. Since 1995, he has been an Associate Professor in the Department of Electrical Engineering, Kure National College of Technology, Hiroshima, Japan. He has been engaged in research work on millimeter-wave integrated circuits and systems based on the nonradiative dielectric waveguide technology.

Dr. Kuroki is a member of the Institute of Electronics, Information, and Communication Engineers (IEICE), Japan, and the Institute of Image Information, and Television Engineers (ITE), Japan.

Masayuki Sugioka was born in Hiroshima, Japan, on October 4, 1977. He received the Associate B.E. degree in electrical engineering from Kure National College of Technology, Hiroshima, Japan, in 1998, and is currently working toward the B.E. degree at Chiba University, Chiba, Japan.

Mr. Sugioka is a member of the Institute of Electronics, Information, and Communication Engineering (IEICE), Japan.

Shinji Matsukawa was born in Hiroshima, Japan, on November 9, 1977. He received the associate B.E. degree in electrical engineering from Kure National College of Technology, Hiroshima, Japan, in 1998, and is currently working toward the B.E. degree at Kyushu Institute of Technology, Kita-Kyushu, Japan.

Mr. Matsukawa is a member of the Institute of Electronics, Information, and Communication Engineering (IEICE), Japan.

Kengo Ikeda was born in Hiroshima, Japan, on March 21, 1976. He received the Associate B.E. degree in electrical engineering from Kure National College of Technology, Hiroshima, Japan, in 1997.

In 1997, he joined the Communication Systems Development Laboratories, Sharp Corporation, Hiroshima, Japan. His recent work is the development of cellular phone systems.

Mr. Ikeda is a member of the Institute of Electronics, Information, and Communication Engineering (IEICE), Japan.

Tsukasa Yoneyama (S'60–M'64–SM'84–F'90), for photograph and biography, see this issue, p. 733.