An Approach to Single Optical Component Antenna Base Stations for Broad-Band Millimeter-Wave Fiber-Radio Access Systems

Ken-Ichi Kitayama, *Senior Member, IEEE*, Andreas Stöhr, *Member, IEEE*, Toshiaki Kuri, *Member, IEEE*, Robert Heinzelmann, Dieter Jäger, *Senior Member, IEEE*, and Yoshiro Takahashi

***Abstract*—To realize a cost-effective and practical antenna base station (BS) for 60-GHz-band millimeter-wave fiber-radio access systems, an approach to *a single optical component BS* is presented in this paper. The external modulation technique will allow to replace the pair of a photodetector (PD) and a laser diode with an external modulator at the BS by an optical transceiver. Two system architectures using different types of optical transceivers are studied in detail: one employs an electroabsorption transceiver (EAT), and the other employs an electroabsorption transceiver/mixer (EATX). The EAT serves simultaneously as a PD and an external light modulator in 60-GHz-band millimeter-wave region. The EATX furthermore acts as an IF-to-RF upconverter and an RF-to-IF downconverter. It will be shown that both system architectures have good prospects to realize cost-effective fiber-radio access systems.**

***Index Terms*—Electroabsorption, optical fiber communication, optical millimeter-wave devices, radio communication, transceivers.**

I. Introduction

MILLIMETER-WAVE fiber-radio access system will meet the demands for a *wireless last hop* to the customers, which can support broad-band and portable services. It will also resolve the scarcity of the available RF resource. The only feasible option to connect the central control station (CS) and the microcellular or picocellular antenna base stations (BSs) will be an optical generation and transport technique of millimeter-wave radio signals over optical fiber links. In the fiber-radio access system, over a thousand BSs are likely to be located under the coverage of a single CS. Therefore, it is foreseen that the low-cost BS is the key to the successful initial deployment of the system. A possible strategy to realize a low-cost BS is a highly centralized CS along with less-equipped BSs, in which expensive optical and millimeter-wave components and equipments are shared with a number of BSs.

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K.-I. Kitayama is with the Department of Electronics and Information Systems, Osaka University, Osaka 565-0871, Japan (e-mail: kitayama@comm.eng.osaka-u.ac.jp).

A. Stöhr, R. Heinzelmann, and D. Jäger are with the Department of Optoelectronics, Gerhard-Mercator-Universität Duisburg, 47057 Duisburg, Germany.

T. Kuri is with the Communications Research Laboratory, Ministry of Posts and Telecommunications, Tokyo 184-8795, Japan.

Y. Takahashi is with the Oki Electric Industry Company Ltd., Tokyo 193-8550, Japan.

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The cost of the BS critically depends upon the system architecture. There have been various system architectures based upon different optical millimeter-wave generation and transport techniques. A desired system has to be the most cost effective among them, while, on the other hand, it satisfies the required performance.

In this paper, an approach to *a single optical component BS* is presented. Two system architectures using different types of optical transceivers are studied; one employs an electroabsorption transceiver (EAT), and the other employs an electroabsorption transceiver/mixer (EATX). A newly developed 60-GHz-band EAT module is introduced, and a full-duplex broad-band millimeter-wave transmission experiment adopting *dual-lightwave* channel allocation for the downlink and uplink will demonstrate that the EAT is a promising candidate for a near-term solution. Although the EATX is still in the phase of proof-of-concept and requires challenges to realize a practical device, an edge will be shown in that it allows an IF-band optical signal to transmit and, thus, alleviates the signal fading caused by the fiber dispersion problem. The proposed two-system architectures will show good prospects to realize the concept of a single optical component at the BS.

II. Single Optical Component Millimeter-Wave Antenna BS

Millimeter-wave generation and transport techniques, thus far investigated, are classified into the following four categories:

1) optical self-heterodyning [1]–[6];
2) external modulation [7]–[11];
3) up- and down-conversion [12]–[15];
4) optical transceiver [16]–[19].

The advantages and disadvantages of the above techniques have been discussed from technical viewpoints in [20]. As our goal will be a single optical component antenna BS, a major step toward this solution is to replace the photodetector (PD) and laser diode pair with an external light modulator at the BS by a single optical transceiver, as shown in Fig. 1. A promising candidate for this is an EAT consisting of a multiquantum well (MQW) III–V semiconductor active waveguide. As shown in Fig. 2, the absorption edge of the MQW waveguide changes with the applied reverse-bias voltage owing to the quantum-confined Stark effect. This yields a large extinction ratio for the light with a wavelength λ_u slightly above the absorption edge. On the other hand, the light with a wavelength λ_d far below the absorption

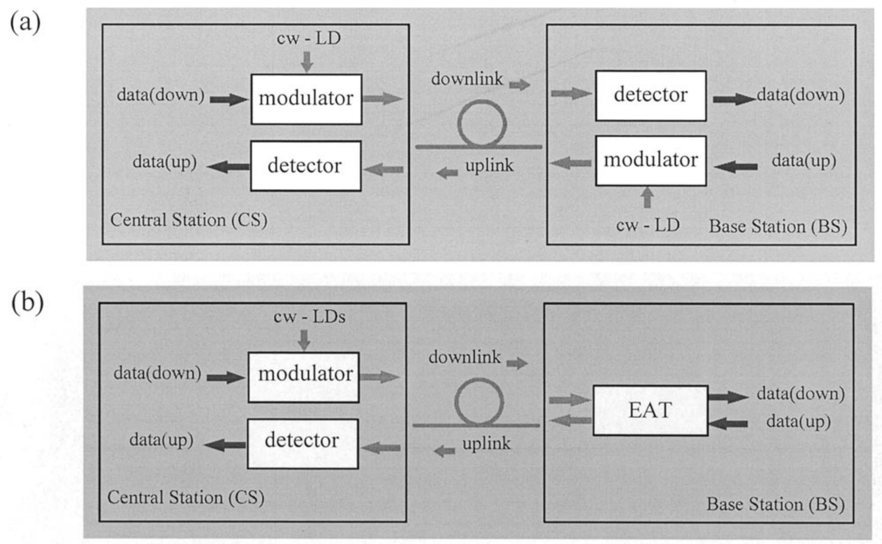


Fig. 1. Architectures of millimeter-wave fiber-radio access systems. (a) Conventional system with a PD and laser diode with an external modulator at the BS. (b) System with a single optical component BS, in which an optical transceiver replaces a pair of optical transmitter and receiver.

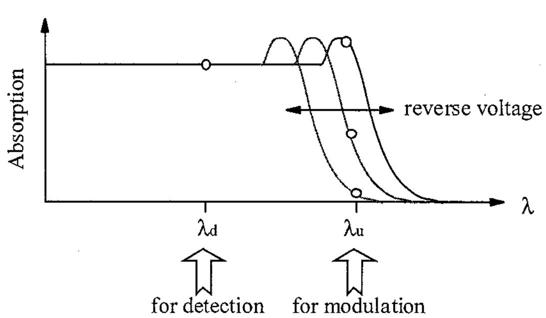


Fig. 2. Absorption of EAT consisting of a MQW III–V semiconductor active waveguide as a function of wavelength. The absorption edge of the MQW waveguide changes with the applied reverse-bias voltage owing to the quantum-confined Stark effect. A large extinction ratio for light with a wavelength λ_u is slightly above the absorption edge while, on the other hand, light with a wavelength λ_d far below the absorption edge is completely absorbed.

edge is completely absorbed. Therefore, a single EAT can simultaneously serve as the optoelectronic (OE) and electrooptic (EO) converter by employing a dual-lightwave channel allocation for the down- and uplink.

Let us turn our focus on the total cost of optical and millimeter-wave components required to construct a BS. In Table I, optical and millimeter-wave components, which consists of a BS, are counted, and the total costs of the required millimeter-wave and optical components located in a BS are summarized for the above four techniques, and the total costs of the BS in the short and long term are evaluated [20]. A reduction in device costs up to a factor of 1/1000 until the year 2010, as introduced in Table I, might not be groundless because there is a good prospect for a drastic price reduction of optical and millimeter-wave components in the near future. The carrying vehicles are intelligent transportation systems (ITS) [21] and fiber-to-the-X (FTTX) [22]. The price reduction of millimeter-wave components is due to the transfer of the monolithic microwave integrated circuit (MMIC) from customized technology to mass-production technology. The price reduction of optical components is already underway, indicated by low-cost optical network units (ONUs) in the customer's premise. Considering a target price of less than \$100.00 for a single BS by 2010, the optical transceiver appears to be the most promising candidate. Therefore, we will focus on the optical transceiver-based solution in the following sections.

III. 60-GHz EAT

For transmission experiments, a 60-GHz-band EAT module, shown in Fig. 3, with individual RF input and output ports has been developed [23]. The EAT chip consists of three regions: a photodetection, passive waveguide, and modulation section. It was grown on an InP substrate and the active region consists of a ten-well tensile strained InGaAsP/InGaAsP MQW core. The EAT employs impedance-matching circuits for both RF ports to minimize the RF return losses around 60 GHz. As shown in Fig. 4, the RF return losses are reduced to −42 dB and −22 dB for the photodetection and modulation ports, respectively. The output optical power of the EAT is shown in Fig. 5(a) versus wavelength for different output port bias voltages. The input port bias and the optical input power were fixed to −1.8 V and 0 dBm, respectively. From this figure, it can be concluded that the optimum wavelength of photodetection is below 1550 nm where the optical power is almost completely absorbed. To identify the optimum modulation performance, the RF insertion loss was measured. In Fig. 5(b), the RF insertion loss is plotted as a function of the reverse dc bias. As can be seen, high modulation is achieved within the wavelength region 1550–1590 nm with an optimum value at 1575 nm.

In the module, fiber-chip coupling is accomplished by a lens system. A further reduction of the EAT component price can be envisaged by eliminating the costly alignment process of the required lens system and the EAT chip. In principle, the lenses are used to match the large circular modal spot

TABLE I
COSTS OF A SINGLE-ANTENNA BS

	Device cost			Numbers of devices				
	Present	Future	Cost reduction (Future/ present)	Optical self-heterodyning	External mod.	Up- & down-conversion E-conv.	Up- & down-conversion O-conv.	Optical trans.
DFB-LD	8,000	8	1/1000	1		1	2	
Mm-wave (60GHz)EAM	30,000	30	1/1000		1		2	1
IF-band EOM	15,000	15	1/1000	1		1	1	
Wavelength DEMUX	10,000	20	1/1000		1	1		1
Photodetector	15,000	15	1/1000	1	1	1	3	
Mm-wave amp.	30,000	30	1/1000	2	2	2	2	2
Mm-wave mixer	5,000	10	1/1000	1		2	1	
Mm-wave osc. (60GHz)	30,000	30	1/1000			1	1	
Mm-wave filter	5,000	10	1/500	1		1	1	
Mm-wave divider	10,000	20	1/500	1				
IF amp.	5,000	10	1/500	1		2	1	
Cost at present (x1000USD)				123	115	163	241	100
Cost in future (USD)				148	125	198	256	110

EOM: Conventional external light modulator

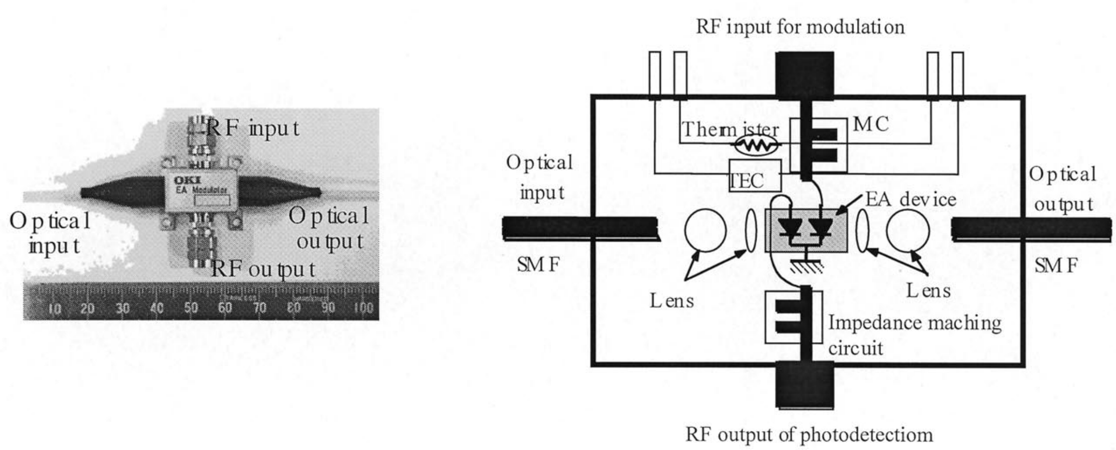


Fig. 3. 60-GHz-band EAT module with individual RF input and output ports. The size of the module is 21 mm (W) $\times$ 13 mm (D) $\times$ 11.3 mm (H). The EAT chip consists of three regions: a photodetection, passive waveguide, and modulation section.

($\sim$10μm) of the standard single-mode fiber (SMF) to the small elliptical mode profile of the EAT waveguide (1–3 μm) for high coupling efficiency. If the lens system is omitted, the fiber could be aligned directly to the chip and, thus, the alignment procedure would drastically be simplified. However, the challenge remains to adiabatically transform the fiber mode to abolish or at least drastically reduce the modal mismatch between the fiber and EAT chip. Here, we demonstrate that this can indeed be achieved by employing a special fabrication process for low-loss tapered SMFs, shown in Fig. 6(a), with a modal spot diameter of 1.5 μm [24]. This straightforward technique neither requires sophisticated fabrication processes, nor any additional lenses and, thus, it offers large potential for further cost reduction. For the experimental verification, a tapered SMF has been coupled to single-section EAT chips. For the simplified fiber alignment, a V-groove is introduced. An SEM picture of the fabricated EAT including the V-grooves is shown in Fig. 6(b). To investigate the fiber-to-chip coupling efficiency, tapered fibers with different modal spot diameters were coupled to the EAT, and the fiber-to-chip coupling efficiency was deduced from photocurrent measurements considering an internal quantum efficiency of 100%. In Fig. 7, the measured and calculated coupling efficiencies are shown versus the modal spot diameter of the tapered fiber. For smaller diameters, the coupling efficiency is increased due to the reduced modal mismatch. From the numerical calculations, a minimum coupling loss of 0.56 dB is obtained. Experimentally, we determined an optimum coupling loss of 1.1 dB for a spot diameter of 1.4 μm. We consider it an excellent value by taking into account the fact that the coupling efficiency for a cleaved SMF with a spot diameter of about 10 μm is only 20%.

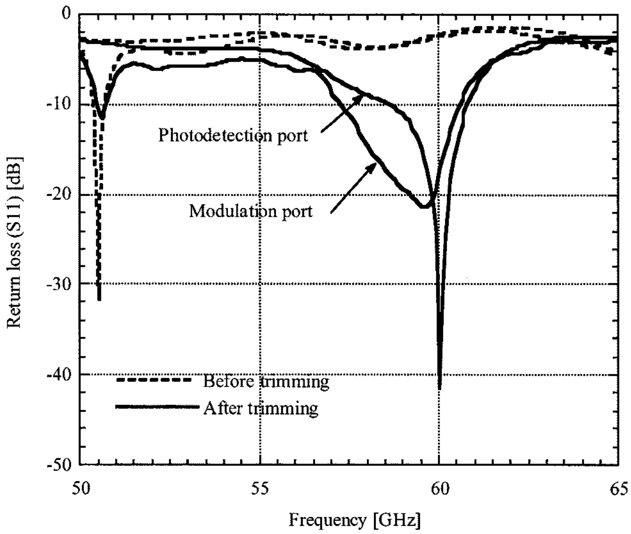
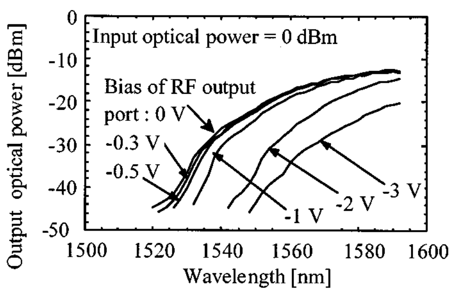
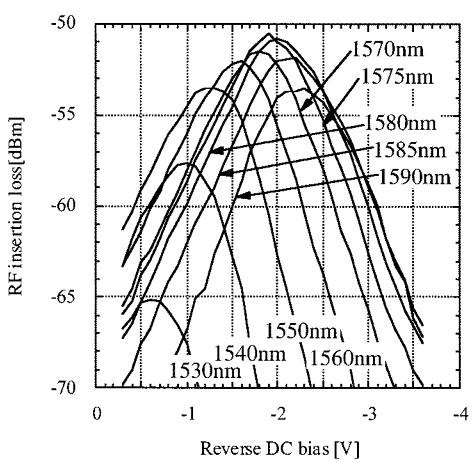


Fig. 4. RF return losses of the PD and modulator ports of the 60-GHz-band EAT as a function of RF.



(a)



(b)

Fig. 5. (a) Output optical power of the EAT as a function of wavelength for various output port bias voltages. The input port bias and optical input power were fixed to -1.8 V and 0 dBm, respectively. (b) RF insertion loss as a function of the reverse bias voltage for various wavelengths.

IV. Fiber-Radio Access System Architecture Employing EAT

The architecture of a 60-GHz-band millimeter-wave fiber-radio access system employing an EAT at the BS is shown in Fig. 8. In the CS, two laser diodes $LD1$ and $LD2$ are used to

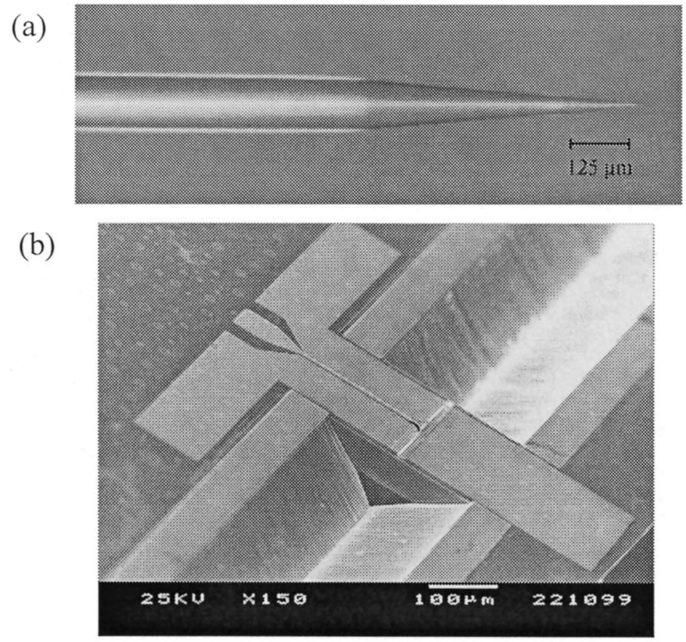


Fig. 6. Simplified fiber alingnment using a V-groove. (a) Low-loss tapered SMF with a modal spot diameter of 1.5 μm. (b) V-groove fabricated on a single-section EAT chip for the coupling with the tapered SMF.

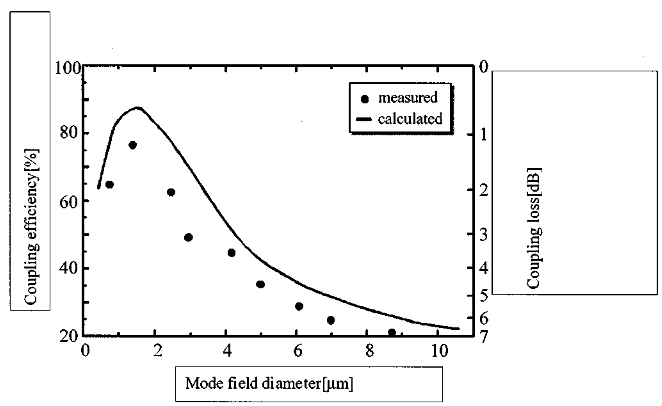


Fig. 7. Measured and calculated coupling efficiencies as a function of the modal spot diameter of the tapered SMF.

generate the optical downlink and uplink carriers, respectively. The downlink carrier ($LD1$) is intensity-modulated with a millimeter-wave subcarrier-multiplexed RF signal using a 60-GHz-band electroabsorption modulator (EAM) [25], and it is delivered to the BS along with the continuous-wave (CW) optical uplink carrier ($LD2$). As discussed above, the dual-lightwave approach requires the downlink wavelength ($LD1$) to be shorter than the uplink wavelength ($LD2$). In the BS, the EAT detects the optical downlink signal and generates a millimeter-wave RF signal, and at the same time, it intensity modulates the optical uplink carrier with the uplink millimeter-wave RF signal and loops it back to CS.

The external modulation basically generates the millimeter-wave optical double-sideband (DSB) signal. One problem with the optical DSB signal transmission in SMF in the wavelength region around 1550 nm is that it causes a periodic fading of the millimeter-wave signal along the fiber

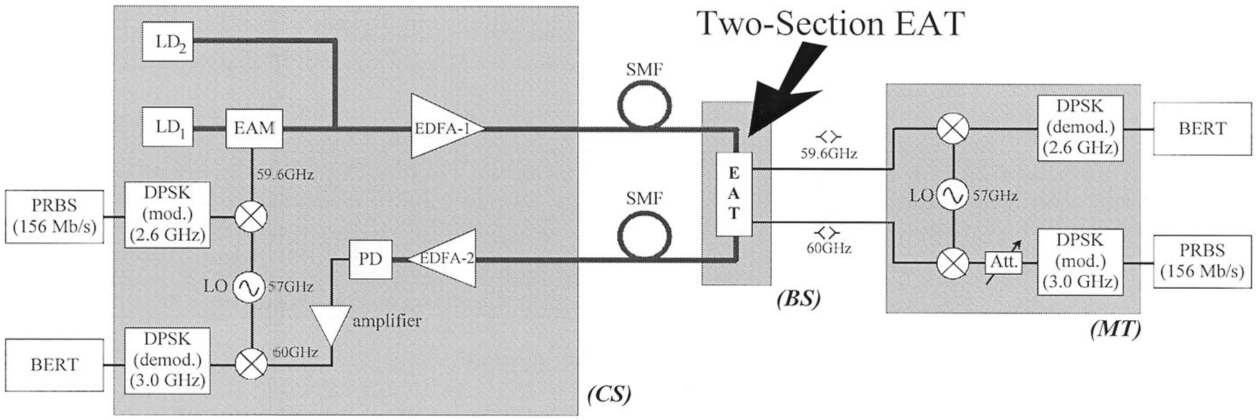


Fig. 8. Architecture of a 60-GHz-band millimeter-wave fiber-radio access system employing an EAT at the BS.

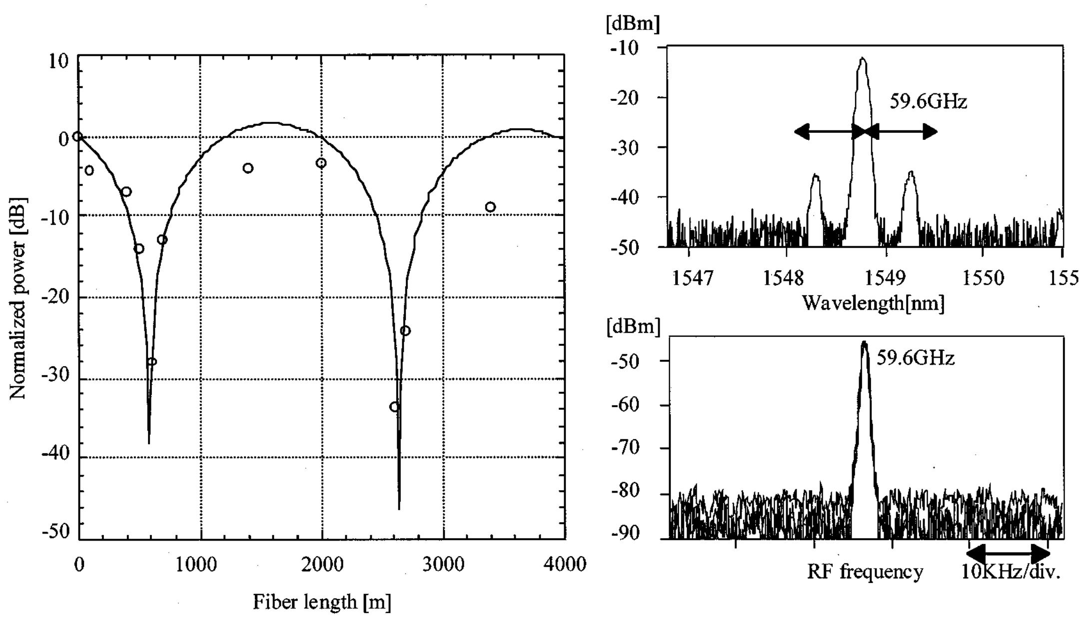


Fig. 9. Experimental and theoretical results of the amplitude of a 60-GHz RF signal generated by the optical DSB signal as a function of the fiber length. The optical spectrum of the DSB signal along with the generated 59.6-GHz millimeter wave is also shown in the inset. The group delay dispersion of the SMF is 17 ps/nm/km.

due to the fiber chromatic dispersion [26]. The fading occurs at the length

$$L = \frac{c}{2D\lambda^2 f_m^2} \tag{1}$$

where D is the fiber dispersion, λ is the wavelength, f_m is the RF carrier frequency, and c is the light velocity in free space. In Fig. 9, the experimental and theoretical results of the amplitude of a 60-GHz RF signal generated by the optical DSB signal are plotted as a function of the fiber length. The optical spectrum of the DSB signal along with the generated 59.6-GHz millimeter wave is also shown in the inset. This will hinder from installing BSs at desired distances from the CS in practical system installation. However, the signal fading has been overcome by compensating the fiber dispersion by inserting into the optical fiber link either a fiber Bragg grating, which has the same dispersion value as the fiber with an opposite sign [27], or an optical phase conjugator [28].

V. Fiber-Radio Access System Architecture Employing EATX

Here, we propose another architecture of a 60-GHz millimeter-wave fiber-radio access system, as shown in Fig. 10. It only requires optical IF transmission and is, thus, almost completely free of the chromatic dispersion effects. There is also just a single optical component at the BS, but it is distinct from the EAT used in the previous system of Fig. 8 in that an EATX is used. The EATX simultaneously acts as a

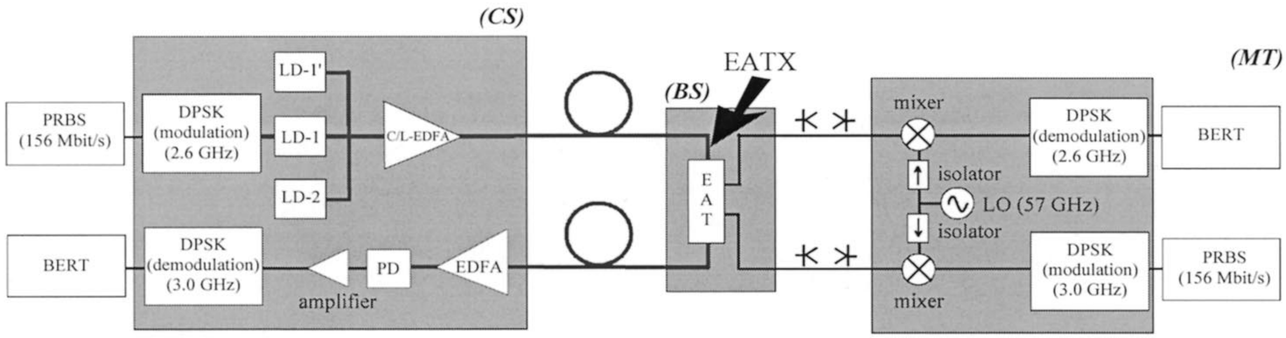


Fig. 10. Architecture of a 60-GHz millimeter-wave fiber-radio access system employing an EATX at the BS.

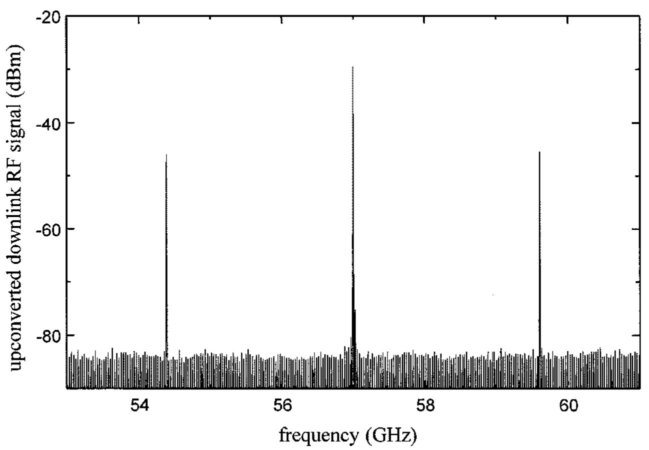


Fig. 11. Electrical output spectra of the DSB signal for the downlink, generated by the EATX.

millimeter-wave PD, an IF-band external modulator, and an IF-to-RF upconvertor and RF-to-IF downconvertor. Optical heterodyning is used to deliver the millimeter-wave RF carrier to the BS. This is intended to alleviate the signal fading due to the chromatic dispersion effect of the above system architecture. Thus, the two lasers $LD1$ and $LD1'$ are located in the CS, whose beat frequency is equal to the desired millimeter-wave RF carrier frequency (57 GHz). $LD1$ is furthermore directly modulated by the downlink IF signal (2.6 GHz). For downlink transmission, to generate the millimeter-wave RF carrier, the EATXand simultaneously upconverts the transmitted IF signal to the millimeter-wave region for subsequent wireless transmission. The measured electrical output spectrum of the EATX for downlink transmission is shown in Fig. 11. The electrical DSB signals centered at 57 GHz with the 2.6-GHz IF modulation frequency. In the uplink transmission, the EATX downconverts the received RF antennas signal (60 GHz) to the IF band (3 GHz) using the generated heterodyne signal at 57 GHz. Furthermore, it performs intensity modulation of the optical uplink carrier $LD2$ with the downconverted IF signal. Finally, the modulated optical uplink signal is received by an IF-band PD in the CS. Both the wavelengths of $LD1$ and $LD1'$ are set to be shorter than the wavelength of the optical uplink carrier ($LD2$). In our approach, the wavelengths of $LD1$ and $LD1'$ are within the optical C-band, whereas the uplink wavelength ($LD2$) is within the optical L-band.

Due to the multifunctional EATX, the system setup is further simplified. As can be seen from Fig. 10, especially the complexity of the CS is simplified in that no millimeter-wave local oscillator (LO), no millimeter-wave mixer, no millimeter-wave amplifier, no millimeter-wave EAM, and no millimeter-wave PD are required. Moreover, it seems feasible to integrate the EATX with a millimeter-wave amplifier and a planar antenna in order to fabricate a single-chip BS. The transmission of IF-band optical signals substantially alleviates the signal fading problem. For example, the first null of the fading can be extended by a factor of 400 resulting in a fiber span extension from 0.6 km at 60 GHz RF signal shown in Fig. 9 to 240 km at 3 GHz IF signal, according to (1).

VI. Full-Duplex Transmission Experiments

In this section, transmission experiments employing the two-port EAT are presented [23]. The experimental system setup, shown in Fig. 8, was used. In detail, the CS consists of two DFB LDs for uplink and downlink, a 60-GHz-band EAM, a 3-dB optical coupler, EDFA1 and 2 for the up- and downlink optical carriers, an optical bandpass filter (BPF), and a high-frequency PD. For simplicity, the BS and the CS are connected with each other by short SMF, and optical attenuators with 5.5-dB attenuation are inserted, equivalent to the fiber's loss of the length of 27.5 km. For downlink transmission, a 155.52-Mb/s differential phase-shift keyed (DPSK) signal centered at an IF of 2.6 GHz are upconverted to 59.6 GHz by an LO in the CS. The optical downlink carrier at 1530 nm is intensity modulated with the millimeter-wave downlink signal using a high-frequency EAM. The optical downlink signal is then amplified by EDFA-1 and transmitted to the BS. In the BS, the optical downlink signal is detected by the two-port EAT. The millimeter-wave signal received in the mobile terminal (MT) is downconverted to IF and demodulated to recover the 155.52-Mb/s data and extract the clock signal. For the uplink transmission, a 155.52-Mb/s DPSK signal centered at an IF of 3 GHz are upconverted to 60-GHz millimeter-wave frequency by the LO in the MT. The optical uplink carrier at 1570 nm is intensity modulated with the millimeter-wave uplink signal by the EAT. The resulting optical uplink signal is looped back to the CS where it is detected by a high-frequency PD. The received RF signal is amplified, downconverted to 3-GHz IF, and demodulated to recover downlink data and clock. For

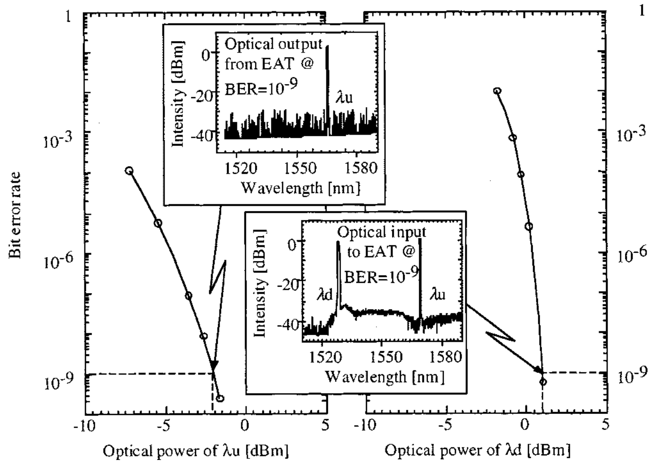


Fig. 12. Measured bit error rates and the optical spectra of uplink and downlink signals. The received optical powers were measured before the EAT for downlink and before the PD for uplink transmission.

measurement purposes, the BS is connected to the MT by coaxial cables.

Fig. 12 shows the measured bit error rates (BERs) and the optical spectra of uplink and downlink signals. Received optical powers were measured before the EAT for downlink and before the PD for uplink transmission. For the photodetection of the downlink signal, a dc bias of -0.3 V was applied to the RF output port of the EAT. For the modulation of optical uplink carrier, a dc bias of -1.8 V and an RF power of 2.2 dBm were applied to the RF input port of the EAT. A BER below 10^{-9} has been achieved for both links. The received optical powers for uplink and downlink transmissions required for $\mathrm{BER} = 10^{-9}$ were -2 and 1 dBm, respectively. For the downlink, the BER abruptly becomes worse as the received optical power decreases. This is due to an interchannel interference from the uplink signal inside the module, although an isolation between RF input and output ports in the module was maintained to be 32 dB.

VII. Conclusion

An approach to *a single optical component at the BS* has been presented in this paper. Two system architectures using different types of optical transceivers have been studied: one employs an EAT and the other employs an EATX. The 60-GHz EAT has been realized, and the 156-Mb/s 60-GHz-band full-duplex transmission experiment adopting dual-lightwave channel allocation for the downlink and uplink has confirmed that the EAT is a promising candidate for a near-term solution. Although the EATX has not yet been implemented into the full-duplex transmission system, it has already been used for heterodyne IF downlink transmission, alleviating the signal fading caused by the fiber dispersion problem. Both system architectures have been shown to provide good prospects to realize cost-effective fiber-radio access systems.

References

[1] J. J. O'Reilly, P. M. Lane, R. Heidemann, and R. Hofstetter, "Optical generation of very narrow linewidth millimeter wave signals," *Electron. Lett.*, vol. 28, pp. 2309–2311, 1992.

[2] L. Goldberg, R. D. Esman, and K. J. Williams, "Generation and control of microwave signals by optical techniques," *Proc. Inst. Elect. Eng.*, pt. J, vol. 139, pp. 288–293, 1992.

[3] U. Gliese, T. N. Nielsen, M. Bruun, E. L. Christensen, K. E. Stubkjær, S. Lindgren, and B. Broberg, "A wideband heterodyne optical phase-locked loop for generation of 3–18 GHz microwave carriers," *IEEE Photon. Technol. Lett.*, vol. 4, pp. 936–938, Aug. 1992.

[4] D. Novak, Z. Ahmed, R. B. Waterhouse, and R. S. Tucker, "Signal generation using pulsed semiconductor lasers for application in millimeter-wave wireless links," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 2257–2262, Sept. 1995.

[5] K. Kitayama, T. Kuri, H. Yokoyama, and M. Okuno, "60 GHz millimeter-wave generation and transport using stabilized mode-locked laser diode with optical frequency DEMUX switch," in *IEEE GLOBECOM'96*, London, U.K., pp. 2162–2169.

[6] R. P. Braun and G. Grosskopf, "Optical feeding of base stations in millimeter-wave mobile communications," in *24th ECOC'98*, vol. 1, Madrid, Spain, pp. 665–666.

[7] K. Kitayama, T. Kuri, and Y. Ogawa, "Error-free optical 156 Mb/s millimeter-wave wireless transport through 60 GHz external modulation," presented at the 1998 Opt. Fiber Conf., San Jose, CA, paper TuC2.

[8] T. Kuri, K. Kitayama, A. Stöhr, and Y. Ogawa, "Fiber-optic millimeter-wave downlink system using 60 GHz-band external modulation," *J. Lightwave Technol.*, vol. 17, pp. 799–806, May 1999.

[9] T. Kuri, K. Kitayama, and Y. Ogawa, "A fiber-optic millimeter-wave uplink incorporating with remotely fed 60 GHz-band optical pilot tone," *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 1332–1337, July 1999.

[10] J. Park, W. V. Sorin, and K. Y. Lau, "Elimination of the fiber chromatic dispersion penalty on 1550 nm millimeter-wave optical transmission," *Electron. Lett.*, vol. 33, pp. 512–513, 1997.

[11] G. H. Smith, D. Novak, and Z. Ahmed, "Technique for optical SSB generation to overcome fiber dispersion penalties in fiber-radio system," *Electron. Lett.*, vol. 33, pp. 74–75, 1997.

[12] R. Helkey, J. C. Twichell, and C. Cox, "A down-conversion optical link with RF gain," *J. Lightwave Technol.*, vol. 15, pp. 956–961, June 1997.

[13] K. J. Williams and R. D. Esman, "Optically amplified downconverting link with shot-noise-limited performance," *IEEE Photon. Technol. Lett.*, vol. 8, pp. 148–150, Jan. 1996.

[14] C. K. Sun, R. J. Orazi, and S. A. Pappert, "Efficient microwave frequency conversion using photonic link signal mixing," *IEEE Photon. Technol. Lett.*, vol. 8, pp. 154–156, MONTH 1996.

[15] K. Kitayama and R. A. Griffin, "Optical downconversion from millimeter-wave to IF-band over 50-km-long optical fiber link using an electroabsorption modulator," *IEEE Photon. Technol. Lett.*, vol. 11, pp. 287–289, Jan. 1999.

[16] L. Noel, D. Wake, D. G. Moodie, D. D. Marcenac, L. D. Westbrook, and D. Nesset, "Novel techniques for high-capacity 60 GHz fiber-radio transmission systems," *IEEE Trans. Microwave Theory Tech.*, vol. 45, pp. 1416–1423, Aug. 1997.

[17] A. Stöhr, K. Kitayama, and D. Jäger, "Full-duplex fiber-optic RF subcarrier transmission using a dual-function modulator/photodetector," *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 1338–1341, July 1999.

[18] A. Stöhr, T. Kuri, K. Kitayama, R. Heinzelmann, and D. Jager, "Full-duplex 60 GHz-fiber-optic transmission," *Electron. Lett.*, vol. 35, no. 19, pp. 1653–1655, 1999.

[19] R. Heinzelmann, T. Kuri, K. Kitayama, A. Stöhr, and D. Jager, "OADM of 60 GHz-millimeter-wave signal in WDM radio-on-fiber ring," presented at the 2000 Optical Fiber Conf., Baltimore, MD, 2000, paper FH4.

[20] K. Kitayama, "Architectural considerations of radio-on-fiber millimeter-wave wireless access systems," *J. Fiber Integrated Opt.*, vol. 19, pp. 167–186, 2000.

[21] L. Raffaelli, "Millimeter-wave automotive radars and related technology," in *IEEE-MTT-S Int. Microwave Symp. Dig.*, 1996, pp. 36–39.

[22] A. Zylbersztejn *et al.*, "Customer ONU: Cost and technology, and standardization issues," in *Proc. Full Services Access Networks Conf.*, London, June 1996.

[23] T. Kuri, K. Kitayama, and Y. Takahashi, "60-GHz-band full-duplex radio-on-fiber system using two-RF-port electroabsorption transceiver," *IEEE Photonic Technol. Lett.*, vol. 12, pp. 419–421, Apr. 2000.

[24] T. Alder, R. Heinzelmann, S. Leonhard, A. Stöhr, and D. Jäger, "Fiber-chip-coupling based on InP-V-groove-technology," in *Proc. LEOS'98 Conf.*, pp. 40–41.

[25] N. Mineo, K. Yamada, K. Nakamura, S. Sakai, and T. Ushikubo, "60-GHz band electroabsorption modulator module," presented at the 1998 Optical Fiber Conf., San Jose, CA, Feb. 1998, paper ThH4.

[26] R. Hofstetter, H. Schmuck, and R. Heidemann, "Dispersion effects in optical millimeter-wave systems using self-heterodyning method for transport and generation," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 2263–2269, Sept. 1995.
[27] K. Kitayama, "Fading-free transport of 60 GHz-optical DSB signal in non dispersion shifted fiber using chirped fiber grating," presented at the Int. Topical Meeting Microwave Photon., Princeton, NJ, 1998, paper WB4.
[28] H. Sotobayashi and K. Kitayama, "Cancellation of signal fading for 60 GHz subcarrier multiplexed optical DSB signal transmission in nondispersion-shifted fiber using midway optical phase conjugation," *J. Lightwave Technol.*, vol. 17, pp. 2488–2497, Dec. 1999.

Ken-Ichi Kitayama (S'75–M'76–SM'89) received the B.E., M.E., and Dr.Eng. degrees in communication engineering from Osaka University, Osaka, Japan, in 1974, 1976, and 1981, respectively.

In 1976, he joined the NTT Electrical Communication Laboratory, where he was engaged in research on fiber optics. During the 1982–1983 academic year, he studied semiconductor lasers and integrated optics at the University of California at Berkeley, as a Visiting Scholar. In 1987, he initiated research on optical signal processings at the NTT Transmission Systems Laboratories. In 1995, he joined the Communications Research Laboratory, Ministry of Posts and Telecommunications of Japan. Since 1999, he has been with Osaka University, where he is currently a Professor in the Department of Electronic and Information Systems, Graduate School of Engineering. His research interests are in photonic networks and fiber-optic wireless communications. He has authored or co-authored over 150 papers in refereed journals, authored two book chapters, and translated one book. He holds 40 patents.

Dr. Kitayama is a member of the Institute of Electronic, Information, and Communication Engineers of Japan, the Japan Society of Applied Physics, and the Optical Society of Japan. He currently serves on the Editorial Board of the IEEE PHOTONICS TECHNOLOGY LETTERS. He received the 1980 Young Engineer Award presented by the Institute of Electronic and Communication Engineers of Japan, and the 1985 Paper Award of Optics presented by the Japan Society of Applied Physics.

Andreas Stöhr (M'97) received the Dipl.-Ing. and Dr.-Ing. degree in electrical engineering from Gerhard-Mercator-Universität Duisburg (GMUD), Duisburg, Germany, in 1991 and 1997, respectively.

Since 1995, he has been a staff member of the Optoelectronics Department, GMUD. In 1998 and 1999, he joined the Communications Research Laboratory (CRL), Ministry of Posts and Telecommunications, Tokyo, Japan, as a Visiting Scientist. His current research interests include the design and fabrication of III/V semiconductor-based microwave photonic devices such as high-speed modulators, PDs, and transceivers, as well as their application in microwave or millimeter-wave fiber-optic transmission systems and optical sensors. He has authored or co-authored over 45 papers in refereed journals and conferences.

Dr. Stöhr is a member of the IEEE Lasers and Electro-Optics Society (IEEE LEOS) and the IEEE Microwave Theory and Techniques Society (IEEE MTT-S). He was a member of the organizing committee for the 1997 International Topical Meeting on Microwave Photonics (MWP'97). He was the recipient of the 1997 Annual Award presented by the Duisburger Universitäts Gesellschaft.

Toshiaki Kuri (S'93–M'96) received the B.E., M.E., and Ph.D. degrees from Osaka University, Osaka, Japan, in 1992, 1994, and 1996, respectively.

In 1996, he joined the Communications Research Laboratory, Ministry of Posts and Telecommunications, Tokyo, Japan. He is mainly engaging in research on optical communication systems.

Dr. Kuri is a member of the Institute of Electronics, Information and Communication Engineers (IEICE), Japan. He was the recipient of the 1998 Young Engineer Award presented by the IEICE.

Robert Heinzelmann received the Dipl.-Ing. degree in electrical engineering from the Gerhard-Mercator-Universität Duisburg (GMUD), Duisburg, Germany, in 1992, and is currently working toward the Ph.D. degree at GMUD. His Dipl.-Ing. thesis concerned the development of planar phased-array antennas for millimeter-wave applications.

He continued these research activities on microwave and millimeter-wave circuits and devices as Junior Research Assistant in the Department of Electrical and Computer Engineering, University of Victoria, Victoria, BC, Canada, in 1993. In 1994, he joined the Department of Optoelectronics, GMUD, where his research interests include optical communication and sensing systems, with the main focus on the development of high-speed III–V semiconductor components, especially waveguide modulators and photomixers. Furthermore, he is in charge of the 250 m^2 clean-room facilities of the department. In 1999, he was with the Communications Research Laboratory, Ministry of Posts and Telecommunications, Tokyo, Japan as Visiting Scientist. He has authored or co-authored over 40 refereed journal and conference papers.

Dieter Jäger (SM'83) received the Diplomphysiker, Dr.rer.nat., and Habilitation degrees in physics from the Westfälische Wilhelms-Universität Münster, Münster, Germany, in 1969, 1974 and 1980, respectively.

From 1974 to 1990, he was Head of a research group at the Institute for Applied Physics, where he became an Associate Professor of physics in 1985. From 1989 to 1990, he was Visiting Professor at the University of Duisburg. Since 1990, he has been on the Faculty of Electrical Engineering, Gerhard-Mercator-Universität Duisburg, Germany, where he is Head of the Department of Optoelectronics and, since 1998, Dean of the faculty. He is an Honorary Professor of the Brasov University, Brasov, Romania. He has authored or co-authored about 300 papers in books, journals, and conferences, and he is a reviewer for several journals. His research interests include microwave optical interaction devices for microwave power generation and transmission, millimeter-wave optical links for broad-band communication technologies, and millimeter-wave electrooptical measuring techniques, and further include nonlinear phenomena in solid-state devices for MMIC applications, as well as nonlinear optics, and optical switching in semiconductors for optoelectronic signal processing. He is also active in the areas of optical neural technology and optoelectronics for medical applications.

Prof. Jäger is a member of the Microwave Photonics Steering Committee, as well as the chair of the German IEEE Lasers and Electro-Optics Society (IEEE LEOS) chapter, the German Physical Society (DPG), the German Vacuum Association (DVG), the German Society of Information Technology (VDE, ITG), and the German Association for Applied Optics (DGaO). He is also a correspondent of the Union Radio-Scientifique Internationale (URSI).

Yoshiro Takahashi received the B.S. and M.S. degree in electrical engineering from Nihon University, Tokyo, Japan, in 1980 and 1982, respectively.

In April 1982, he joined the Oki Electric Industry Company, Tokyo, Japan, where he was involved in the development of microelectronics technology. His current activities are in the area of RF/high-speed subsystems, especially millimeter-wave band subsystems.

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