Optical Heterodyne Detection of Millimeter-Wave-Band Radio-on-Fiber Signals With a Remote Dual-Mode Local Light Source

Toshiaki Kuri, *Member, IEEE*, and Ken-ichi Kitayama, *Senior Member, IEEE*

***Abstract*—A novel technique for optical heterodyne detection of a millimeter-wave radio-on-fiber signal using a remote dual-mode local light is proposed. Although a free-running dual-mode local light is used, the proposed technique is in principle free from laser phase noise. Since only two components of the optical signal are selected by the local light to demodulate themselves, this technique is also theoretically immune from the fiber-dispersion effect, even if the transmitted optical signal is in the double-sideband format. We derive the theoretical limit of the system performance and then experimentally demonstrate a 25-km-long fiber-optic transmission and the optical heterodyne detection of a 59.6-GHz radio-on-fiber signal with 155.52-Mb/s differential-phase-shift-keying formatted data.**

***Index Terms*—Analog systems, electroabsorption, heterodyning, millimeter-wave communication, optical fiber communication, optical fiber dispersion, optical noise, phase noise.**

I. INTRODUCTION

IN ORDER to support future broad-band wireless services, we have reported millimeter-wave radio-on-fiber systems using a 60-GHz-band electroabsorption modulator (EAM) [1], [2]. To receive optical power great enough to get high transmission quality, the use of some optical amplifiers is necessary in the link. In analog optical systems, such as radio-on-fiber applications, however, accumulated amplified spontaneous emission (ASE) noise from the amplifiers can no longer be further removed, and the noise fatally affects the system performance. From a theoretical viewpoint, coherent detection with a remote local light has higher sensitivity to a received optical signal than to direct detection [3]. Therefore, we expect that the coherent detection technique can avoid the use of optical amplifiers. When we consider optical heterodyne detection with a remote local light, laser phase noise, and polarization mismatch cause the degradation of system performance. Since polarization mismatch is a common problem for optical coherent detection, we concentrate on the reduction of laser phase noise.

In this paper, a novel technique of optical heterodyne detection of a millimeter-wave radio-on-fiber signal using a remote dual-mode local light source is proposed. It will be shown that the system performance is in principle completely free from the laser phase noise not only of a transmitting laser but also of the free-running remote local laser. Since only two components of the optical signal are selected by the local light to demodulate themselves, this technique is also theoretically immune from the fiber-dispersion effect which causes the signal fading, even if the transmitted optical signal is in double-sideband (DSB) format. Although some dispersion-free systems [4], [5] have been proposed, they have never essentially solved the ASE problem. We present the principle with a mathematical description of signals in the proposed technique, and then derive the theoretical limit of the system performance. To confirm the principle of the proposed technique, a 25-km-long fiber-optic transmission and the optical heterodyne detection of a 59.6-GHz radio-on-fiber signal with 155.52-Mb/s differential-phase-shift-keying (DPSK) data are demonstrated without any serious laser phase noise and fiber-dispersion effects. To our knowledge, for the first time, it is not only theoretically analyzed but also experimentally demonstrated that a radio-on-fiber signal can be optically heterodyne-detected with a dual-mode local light.

II. PRINCIPLE

A. Mathematical Description

Fig. 1 shows the block diagram of the proposed optical heterodyne detection technique.

An optical carrier from a single-mode light source is written as

$$e_{c1}(t) \propto \sqrt{2P_{c1}} \cdot \exp\{j\varphi_{c1}(t)\} \tag{1}$$

$$\varphi_{c1}(t) = 2\pi f_{c1} t + \phi_{c1}(t) \tag{2}$$

where P_{c1}, f_{c1}, and $\phi_{c1}(t)$ are the power, the center frequency, and the phase noise of the optical carrier, respectively. Let an RF signal be $e_{\mathrm{RF}}(t) = V_{\mathrm{RF}} \exp[\{j2\pi f_{\mathrm{RF}} t + \theta(t)\}]$, where V_{RF}, f_{RF}, and $\theta(t)$ represent the amplitude, the carrier frequency, and the phase-modulated data of the RF signal, respectively. Taking into account the fiber-dispersion effect, the modulated optical signal after the propagation in the optical fiber of the length L is generally written as

$$e_s(t, L) \propto \sqrt{2P_{c1}} \cdot \sum_{n=-\infty}^{\infty} a_n \cdot e^{j\varphi_{s,n}(t, L)} \tag{3}$$

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T. Kuri is with the Basic and Advanced Research Division, Communications Research Laboratory, Koganei, Tokyo 184-8795, Japan (e-mail: kuri@crl.go.jp).

K. Kitayama is with the Department of Electronics and Information Systems, Graduate School of Engineering, Osaka University, Suita, Osaka 565-0871, Japan.

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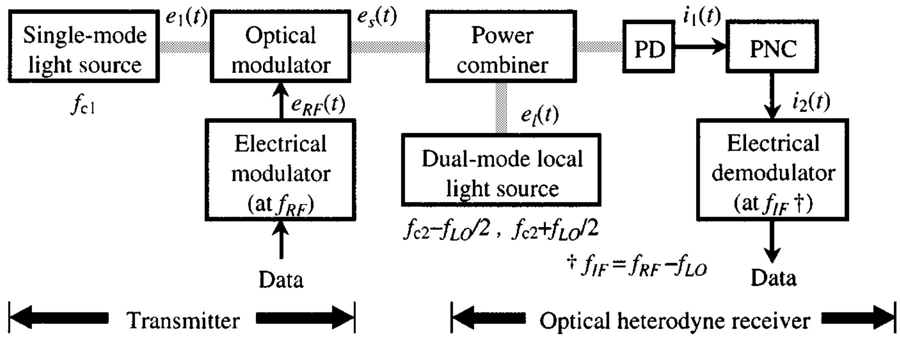

Fig. 1. Block diagram of proposed technique.

$$\begin{aligned}\varphi_{s,n}(t, L) =& \varphi_{c1}(t) + n\varphi_{\rm RF}(t) - \beta(f)\cdot L\\ \simeq& 2\pi(f_{c1}+nf_{\rm RF})(t-\beta_1 L) + n\theta(t-\beta_1 L)\\ &+ \phi_{c1}(t-\beta_1 L) - \beta_2(2\pi n f_{\rm RF})^2\cdot L/2\\ &+ (2\pi f_{c1}\cdot\beta_1 - \beta_0)\cdot L. \end{aligned}\tag{4}$$

The propagation constant $\beta(f)$ is approximated as $\beta_0 + \beta_1 2\pi(f - f_{c1}) + \beta_2\{2\pi(f-f_{c1})\}^2/2$ [6]. $\beta_1 L$ corresponds to the group delay time, and $\beta_2 = -\lambda^2 D/2\pi c$ is satisfied, where D, λ, and c are the dispersion, the wavelength in the fiber, and the velocity in the vacuum, respectively. Note that the last term in (4) is constant and independent of time, and the second-to-last term represents the fiber-dispersion effect. If intensity modulation is performed and the modulation index, $m_{\rm IF}$, is small, the Fourier coefficients are approximated as [7]

$$a_0 \simeq \left[1 - (m_{IM}/4)^2\right]/2 \tag{5}$$

$$a_{\pm n} \simeq (-1)^{n-1}\sqrt{\frac{1}{2}}\,\frac{(2n-3)!!}{n!}\,\left(\frac{m_{IM}}{4}\right)^n \tag{6}$$

where $(2n+1)!! \equiv 1\cdot 3\cdots(2n+1)$ for $n > 0$. When $V_{\rm RF}$ ($\propto m_{IM}$) is small, $e_s(t)$ becomes $E_{c1}\cdot\{a_{-1}\cdot e^{j\varphi_{s,-1}(t,L)} + a_0\cdot e^{j\varphi_{s,0}(t,L)} + a_1\cdot e^{j\varphi_{s,1}(t,L)}\}$.

The free-running dual-mode local light having a frequency separation of $f_{\rm LO}$ is used to detect the radio-on-fiber signal. Here, the dual-mode light source is considered to have a frequency separation that is either highly stabilized or jitter-free and is written as

$$e_l(t) \propto \sqrt{P_{c2}}\cdot\left\{e^{j\varphi_{l-}(t)} + e^{j\varphi_{l+}(t)}\right\}\Big/\sqrt{2} \tag{7}$$

$$\varphi_{l-}(t) = 2\pi(f_{c2} - f_{\rm LO}/2)t + \phi_{c2}(t) \tag{8}$$

$$\varphi_{l+}(t) = 2\pi(f_{c2} + f_{\rm LO}/2)t + \phi_{c2}(t) \tag{9}$$

where P_{c2}, f_{c2}, and $\phi_{c2}(t)$ are the power, the center frequency, and the phase noise of the dual-mode local light, respectively. The dual-mode local light is combined with the received optical signal, as shown in Fig. 2. We assume that the polarizations between the received optical signal and the optical local reference are matched. Then, the photocurrent becomes

$$\begin{aligned}i_1(t) =& \mathcal{R}\sqrt{2P_{c1}P_{c2}}a_0 e^{j(\varphi_{s,0}(t,L) - \varphi_{l-}(t))}\\ &+\mathcal{R}\sqrt{2P_{c1}P_{c2}}a_1 e^{j(\varphi_{s,1}(t,L) - \varphi_{l+}(t))}\\ &+\mathcal{R}\sqrt{2P_{c1}P_{c2}}a_0 e^{j(\varphi_{l+}(t) - \varphi_{s,0}(t,L))}\\ &+\mathcal{R}\sqrt{2P_{c1}P_{c2}}a_{-1} e^{j(\varphi_{l-}(t) - \varphi_{s,-1}(t,L))} + \cdots. \end{aligned}\tag{10}$$

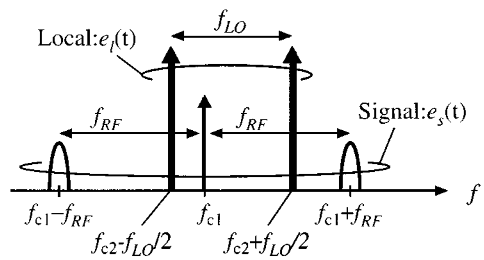

Fig. 2. Optical spectra of signal $e_s(t)$ and local $e_l(t)$.

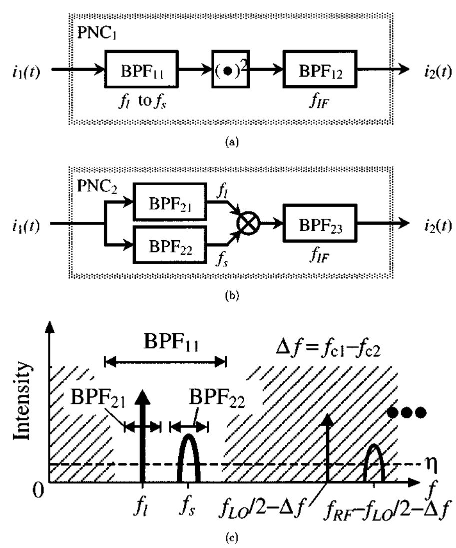

Fig. 3. PNCs: (a) with square-law detector (PNC$_1$) and (b) with multiplier (PNC$_2$). (c) Photodetected signals and passbands of BPF$_{11}$, BPF$_{21}$, and BPF$_{22}$.

Note that $\mathcal{R}$ is the responsivity of a photodetector (PD), and we focus on the two phase components

$$\begin{aligned}\varphi_{s,0}(t, L) - \varphi_{l-}(t) =& 2\pi f_l(t-\beta_1 L) + \Delta\phi_c(t, L)\\ &+ \{2\pi f_l\beta_1 - \beta_0\}L \end{aligned}\tag{11}$$

$$\begin{aligned}\varphi_{s,1}(t, L) - \varphi_{l+}(t) =& 2\pi f_s(t-\beta_1 L) + \Delta\phi_c(t, L)\\ &+ \theta(t-\beta_1 L) - \beta_2(2\pi f_{\rm RF})^2 L/2\\ &+ \{2\pi f_s\beta_1 - \beta_0\}L \end{aligned}\tag{12}$$

where $f_l \equiv \Delta f + f_{\rm LO}/2$, $f_s \equiv \Delta f + f_{\rm RF} - f_{\rm LO}/2$, $\Delta f \equiv f_{c1} - f_{c2}$, and $\Delta\phi_c(t, L) \equiv \phi_{c1}(t-\beta_1 L) - \phi_{c2}(t)$

There are two possible configurations of the PNC: 1) with an electrical square-law detector (PNC$_1$) and 2) with an electrical

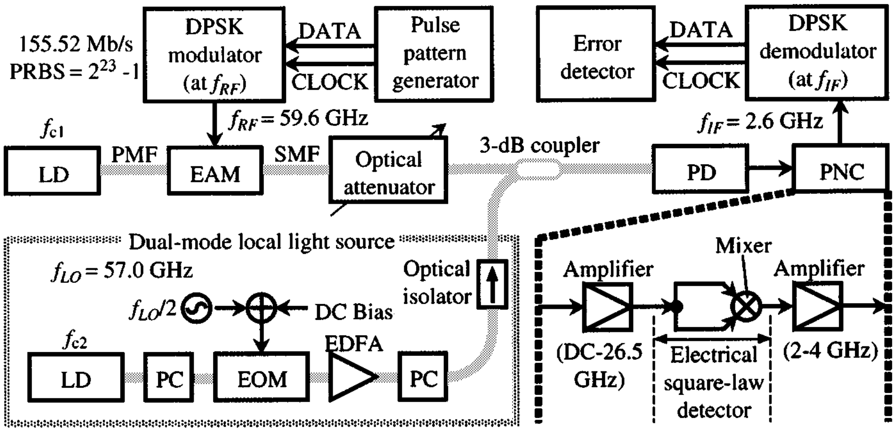

Fig. 4. Experimental setup.

multiplier (PNC_2) [8], as shown in Fig. 3. In Fig. 3(a), BPF_{11} in PNC_1 filters out two components at f_l and f_s simultaneously. They are squared by the square-law detector, and then the down-converted signal at $f_{\rm IF}$ [$\equiv f_{\rm RF} - f_{\rm LO}$] is filtered out by BPF_{12}

$$i_2(t) \propto \mathcal{R}^2 P_{c1} P_{c2} a_0 a_1 e^{j\varphi_{\rm IF}(t,\,L)}/2 \tag{13}$$

$$\begin{aligned}\varphi_{\rm IF}(t,\,L) =& \{\varphi_{s,1}(t,\,L) - \varphi_{l+}(t)\} - \{\varphi_{s,0}(t,\,L) - \varphi_{l-}(t)\}\\ =& 2\pi f_{\rm IF}(t - \beta_1 L) + \theta(t - \beta_1 L)\\ &- \{\beta_0 - 2\pi f_{\rm IF}\beta_1 + \beta_2(2\pi f_{\rm RF})^2/2\}L.\end{aligned} \tag{14}$$

In PNC_2, two components at f_l and f_s are filtered out each by BPF_{21} and BPF_{22}, respectively, as shown in Fig. 3(b). They are multiplied by each other, and then the down-converted signal at $f_{\rm IF}$, $i_2(t)$, is filtered out by BPF_{23}, which is identical to BPF_{12}. Also, in this case, $i_2(t)$ becomes the same signal as expressed in (13), except for half of the amplitude. The difference of PNC_1 and PNC_2 is the amount of the noise put into the square-law detector or the multiplier, because of the difference of bandwidths of BPF_{11}, BPF_{21}, and BPF_{22}, as shown in Fig. 3(c). This will cause an absolute amount of noise due to a *noise* $\times$ *noise* term included in PNC_1 output which is larger than that in PNC_2 output. However, the *noise* $\times$ *noise* term is usually negligible in a practical case, in which the signal-to-noise ratio (SNR) is relatively high in order to transmit data with high quality. Therefore, the system performances for the systems with PNC_1 and PNC_2 will be almost the same.

From the above, we can now discuss the features. First, no laser phase-noise term remains in (13) and (14). This means that this detection technique is, in principle, free from the laser phase noise. Second, the last term in (14) represents the phase delay for the fiber length of L and is constant. If the RF signal is DPSK-encoded, the fiber-dispersion effect does not seriously affect the transmission quality because only two optical components, i.e., one single-sideband (SSB) component and carrier, are detected. Third, the filtering is not performed in the optical domain but in the electrical domain to select the desired signal components. Since the frequency stability and controllability of lasers have recently progressed in conjunction with the development of dense wavelength-division-multiplexing (WDM) technologies, this technique will be able to provide the fine and tunable filtering of the desired optical components by using matured electrical filters.

B. Theoretical System Performance

We will now derive the SNR of the down-converted signal, $i_2(t)$, in the proposed system. As shown in the previous section, there was no fiber-dispersion effect in the proposed demodulation, and therefore we will omit $\beta(f)$ below.

Let us rewrite the photodetected signal with no data ($\theta(t) \equiv 0$) and the local components in the real part as follows:

$$s(t) = \mathcal{R}\sqrt{P_{c1}P_{c2}/2}\,a_1 \cos\left(2\pi f_s t + \Delta\phi(t)\right) \tag{15}$$

$$l(t) = \mathcal{R}\sqrt{P_{c1}P_{c2}/2}\,a_0 \cos\left(2\pi f_l t + \Delta\phi(t)\right). \tag{16}$$

Under the shot-noise limited condition, the noise spectral density is given by $\eta = e\mathcal{R}P_{c2}(1 + P_{c1}/2P_{c2})/4$. If the input to the multiplier is optimally band-limited, then the following SNR is derived:

$$\frac{S}{N} = \frac{\alpha P_{c1}}{B_{\rm IF}} \cdot \frac{a_0^2 a_1^2}{a_0^2 + a_1^2} \cdot \frac{1}{2(1 + P_{c1}/2P_{c2})}. \tag{17}$$

Here, $\alpha[=\mathcal{R}/e]$ is the sensitivity of the PD. Under the local shot-noise limited environment ($P_{c2} \gg P_{c1}$), the theoretical limit of SNR is given by

$$\frac{S}{N} = \frac{1}{2} \cdot \frac{\alpha P_{c1}}{B_{\rm IF}} \cdot \frac{a_0^2 a_1^2}{a_0^2 + a_1^2}. \tag{18}$$

Let us consider a conventional intensity modulation/direct detection (IM/DD) system using optical SSB format [2]. Assuming that the optical signal is modulated by the same transmitter shown in Fig. 1(a), the two interesting optical components with no data are expressed as

$$e_{s1}(t) = \sqrt{G}E_{c1}a_1 \cdot e^{j(\varphi_{c1}(t) + 2\pi f_{\rm RF} t)} \tag{19}$$

$$e_{s0}(t) = \sqrt{G}E_{c1}a_0 \cdot e^{j\varphi_{c1}(t)} \tag{20}$$

where G is the gain of an optical amplifier with the spontaneous emission coefficient of $n_{\rm sp}$ [6]. If the gain of the optical am-

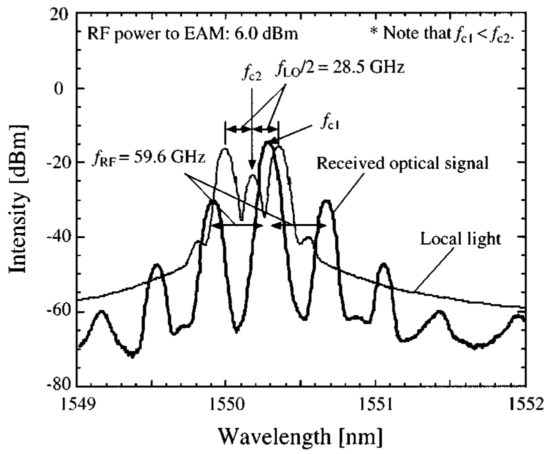

Fig. 5. Measured optical spectra.

plifier is large enough to suppress the other noise components ($G \gg 1$), then the theoretical limit of the SNR is given by

$$\frac{S}{N} = \frac{1}{2n_{\rm sp}} \cdot \frac{\alpha P_{c1}}{B_{\rm IF}} \cdot \frac{a_0^2 a_1^2}{a_0^2 + a_1^2}. \tag{21}$$

From (18) and (21), we can see that the SNR for the proposed detection is improved by a factor of $n_{\rm sp}$.

III. Experiment

A. Experimental Setup

Fig. 4 shows the experimental setup for the proof-of-concept. The optical system consists of a distributed feedback laser diode (LD_1), a 60-GHz-band EAM [2], an optical 3-dB coupler, a tunable laser diode (LD_2), two polarization controllers (PCs), an $LiNO_3$ modulator (EOM), an erbium-doped fiber amplifier (EDFA), an optical isolator, and a PD. The PNC based on the square-law scheme consists of two electric amplifiers and an electric mixer (the bandwidth of the RF, LO, and IF ports are 5–18, 5–18, and dc–3 GHz, respectively). An optical carrier is intensity modulated with a 59.6-GHz signal by the EAM. The RF signal is DPSK-encoded at 155.52 Mb/s (PRBS $= 2^{23} - 1$). An optical local tone, which is modulated with a 28.5-GHz $[=f_{\rm LO}/2]$ sinusoidal wave at the dc bias to enable the suppression of the carrier, and the optical signal are combined, and then optically heterodyne-detected. The EDFA was used only to amplify the optical local tone. In the PNC, the photodetected signal is amplified by the first electrical amplifier (dc–26.5 GHz), power-divided, multiplied, and then amplified again by the next amplifier (2–4 GHz). Finally, the 2.6-GHz IF signal after the mixer is DPSK-demodulated.

B. Experimental Results

In Fig. 5, the thick and thin lines represent the measured optical spectra for the optical signal and the dual-mode local tone, respectively. The wavelengths of LD_1 and LD_2 were 1550.27 nm $[=c/f_{c1}]$ and 1550.17 nm $[=c/f_{c2}]$, respectively. The optical-insertion losses of the EAM at the bias of -1.5 V and the EOM at the bias of 1.5 V were 11 and 25 dB, respectively. In the optical local tone, the carrier still remains, but it can be removed with the present allocation of f_{c1} and f_{c2}.

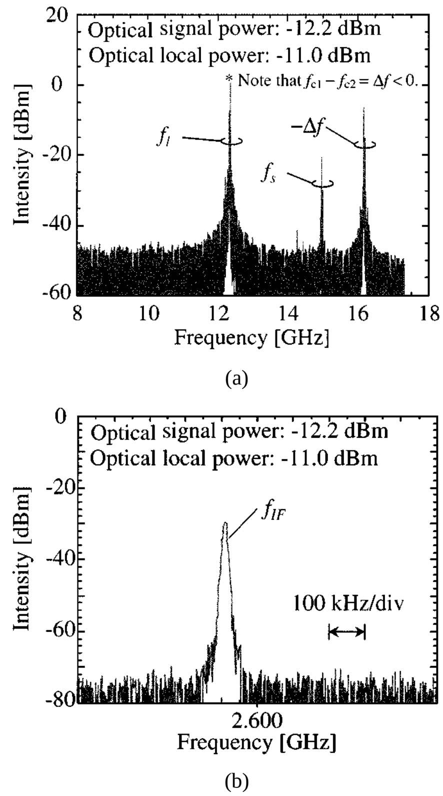

Fig. 6. Measured spectra (a) before and (b) after mixer.

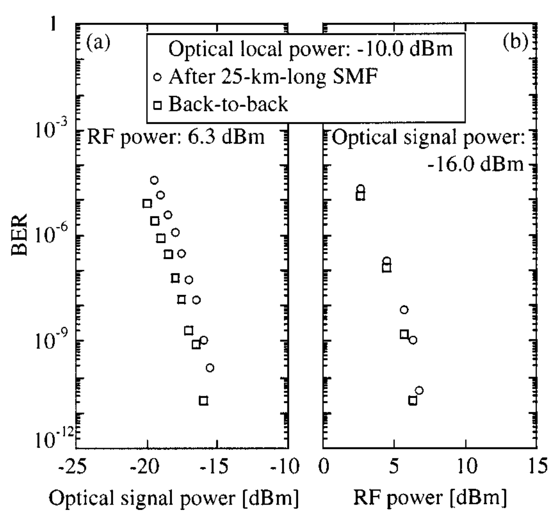

Fig. 7. BERs versus: (a) optical signal power and (b) RF power.

As shown in Fig. 6(a), the photodetected signals appear at around 12.4 GHz $[=f_l]$, 15.0 GHz $[=f_s]$, and 16.2 GHz $[=-\Delta f]$. Note that $f_{c1} < f_{c2}$. From the linewidths, large phase noises caused by the individually driven LD_1 and LD_2 were observed. In Fig. 6(b), however, a 2.6-GHz IF signal was stably generated. The observed linewidth was less than 30 Hz and the measured SSB phase noise was less than -73 dBc/Hz at 10 kHz apart from the carrier, despite the fact that the linewidths of LD_1 and LD_2 were 5 MHz and 100 kHz, respectively. Hence, the phase-noise cancellation was successfully demonstrated.

We also measured the BERs as a function of the optical signal power to the PD or the RF power to the EAM, both for the 25-km-long SMF transmission and for the back-to-back, as shown in Fig. 7. Optical local power to the PD was -10.0 dBm. From Fig. 7(a), the minimum optical signal power to achieve a BER of 10^{-9} was -16.0 dBm, where the RF input power to the EAM was 6.3 dBm. No BER floor was observed. Compared with the back-to-back case, the small power penalty was presumably due to the polarization matching error. From Fig. 7(b), the minimum RF input power to ahieve a BER of 10^{-9} after the SMF transmission was also 6.3 dBm, where the optical signal power to the PD was -16.0 dBm. Again, no BER floor was observed. Compared with the back-to-back case, no serious power penalty was observed.

Finally, a two-mode distributed-Bragg-reflector mode-locked laser diode (DBR-MLLD) [9] will be a candidate for a dual-mode local light source because of the simpler configuration and the higher output power.

IV. Conclusion

A novel optical heterodyne detection technique of a millimeter-wave-band radio-on-fiber signal using a remote dual-mode local light source has been proposed. Although the free-running dual-mode local light is used, the proposed detection technique is in principle free from the laser phase noise. Moreover, this technique is theoretically immune from the fiber-dispersion effect, even if the transmitted optical signal is in DSB format. The principle along with the mathematical description has been described, and the theoretical limit of the system performance has also been derived. To confirm the principle, the 25-km-long fiber-optic transmission and the optical heterodyne detection of a 59.6-GHz radio-on-fiber signal with 155.52-Mb/s DPSK data was successfully demonstrated without serious laser phase noise and fiber-dispersion effects. To our knowledge, it has been not only theoretically analyzed but also experimentally demonstrated for the first time that a radio-on-fiber signal can be optically heterodyne-detected with a dual-mode local light. We expect that use of this technique will lead to the realization of radio-on-fiber systems without additive optical noise.

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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 Communications Research Laboratory, Ministry of Posts and Telecommunications, Tokyo, Japan, where he is mainly engaged in the 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 from the IEICE.

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. From 1982 to 1983, he spent a year as a Research Fellow at the University of California at Berkeley. In 1995, he joined the Communications Research Laboratory, Tokyo, Japan. Since 1999, he has been with Osaka University, where he is currently the Professor of the Department of Electronic and Information Systems Engineering, Graduate School of Engineering. His research interests include photonic networks and fiber-optic wireless communications. He has authored or co-authored over 140 papers in refereed journals, two book chapters, and translated one book. He holds over 30 patents.

Prof. Kitayama is a member of the the Institute of Electronic, Information and Communication Engineers (IEICE), Japan, the Japan Society of Applied Physics, and the Optical Society of Japan. He currently serves on the Editorial Boards of the IEEE Photonics Technology Letters and the IEEE Transactions on Communications. He was the recipient of the 1980 IEICE Young Engineer Award f and the 1985 Paper Award of Optics presented by the Japan Society of Applied Physics.