Coherent Fiber-Optic Microcellular Radio Communication System Using a Novel RF-to-Optic Conversion Scheme

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***Abstract*— This paper proposes a new coherent fiber-optic microcellular radio communication system using a novel RF-to-Optic conversion scheme. In this system a radio signal is converted into an optical signal with the same modulation format coherently transmitted through a wide-band optical fiber without any baseband demodulation and modulation. The theoretical analysis and computer simulation of transmission performances of radio QPSK and QAM signals clarify that the proposed system is superior to the fiber-optic radio communication system using conventional coherent analog optical links.**

I. Introduction

RECENT developments in fiber-optics and cellular radio communications have been spawning many new communication systems. The fiber-optic microcellular radio communication system, which harmonizes these technologies, has been extensively researched and demonstrated [1]–[7] because of its features, such as the flexible use of radio base station for various types of new services, the high absorption for traffic fluctuation, the low equipment cost for base stations, and the easy execution of handover among microcells.

With regard to optical modulation schemes in the fiber-optic microcellular radio communication system, intensity modulation/direct detection (IM/DD) has been demonstrated mainly from the viewpoint of its technical and economical implementation [1]–[7]. However, it is foreseen that the demands for the high-bit-rate multimedia services based on Broadband Integrated Services Digital Networks (B-ISDN) will increase in the future personal wireless communications, therefore much better transmission performance will be required for the optical link in the fiber-optic microcellular radio communication system. A possible solution to improve the performance of the optical link is the coherent optical transmission systems [8]–[12]. Coherent optical transmission systems can approach the shot-noise-limited performance with sufficient local light power and a balanced-mixing photodetector [13]–[15], make up optical-frequency division multiplexed (OFDM) signals with the high-frequency resolution, and detect the frequency or phase of the optical carrier. However, since typical coherent systems are essentially sensitive to the laser phase noise, the transmitting or local oscillator laser should have higher spectral purity than that in the IM/DD system.

In coherent analog optical transmission systems for radio signals such as microwave or millimeter-wave signal, conventional optical modulation methods, i.e., amplitude modulation (AM), frequency modulation (FM), and phase modulation (PM), have been usually considered. For example, the subcarrier multiplexed PM heterodyne detection system has been demonstrated [10], [11] for video distribution and the dynamic range performances of AM, FM, and PM systems have been investigated [12].

In this paper, we propose a new coherent fiber-optic microcellular radio communication system using a novel RF-to-Optic conversion scheme by the use of the electrooptic effect, which has been applied as an optical frequency shifter [16]–[18] or an optical frequency modulator [19]. The most distinctive feature of the proposed system is that a microwave or millimeter wave radio signal is converted into an optical signal with the same modulation format without any baseband demodulation and modulation. In the proposed system, for example, a quarternary phase shift keying (QPSK) or quadrature amplitude modulated (QAM) radio signal received at the base station of microcell is converted into an optical QPSK or QAM signal, transmitted to the optical receiver at the central station, and transformed again into RF signal in a desired frequency band by the optical heterodyne detection. In other words, the proposed system, which is a coherent RF-to-optical link conversion system, is thus quite different from conventional coherent analog optical transmission systems.

The carrier-to-noise power ratio (CNR) performance of the optical link is analyzed and the symbol error rate (SER) performances in the case of QPSK and QAM transmission are examined by computer simulation. As a result, it is concluded that the proposed system is superior to the fiber-optic radio communication system using conventional coherent analog optical links.

In Section II, the principle of the RF-to-Optic conversion scheme is described. In Section III, we show the configura-

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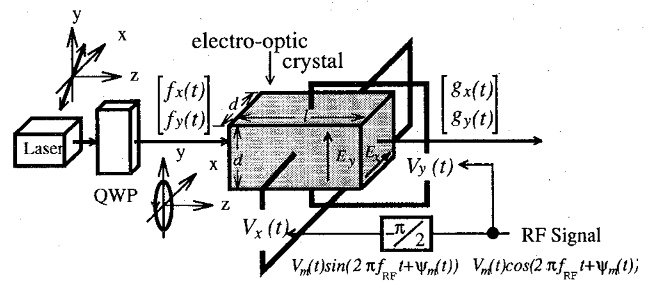

Fig. 1. Configuration of the RF-to-Optic conversion scheme.

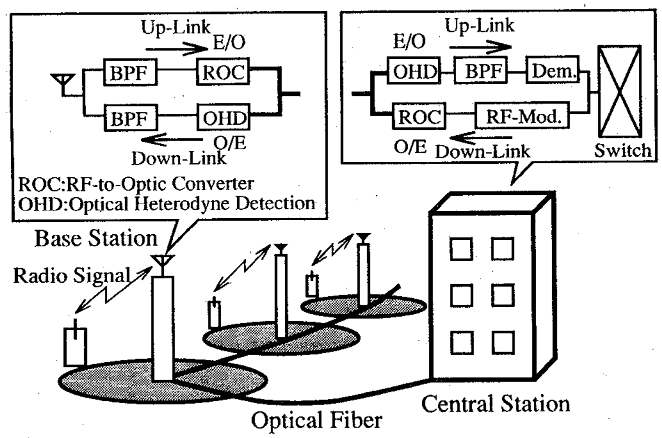

Fig. 2. Coherent fiber-optic microcellular radio comunication system using RF-to-Optic conversion.

tion of the proposed coherent fiber-optic microcellular radio communication system using this novel conversion scheme. In Section IV, we investigate the CNR performances of the optical link and examine the SER performances of radio signals such as QPSK and QAM signals by theoretical analysis and computer simulation. Finally, conclusions are presented in Section V.

II. Principle of RF-to-Optic Conversion Scheme

Fig. 1 illustrates the configuration of the RF-to-Optic conversion scheme. When the driving voltages of the electrooptic crystal along the x and y axes, $V_x(t)$ and $V_y(t)$, are mutually orthogonal RF signals as

$$V_x(t) = V_m(t)\,\sin\left[2\pi f_{\rm RF}t + \psi_m(t)\right] \tag{1}$$

and

$$V_y(t) = V_m(t)\,\cos\left[2\pi f_{\rm RF}t + \psi_m(t)\right] \tag{2}$$

where $V_m(t)$, f_{RF} and $\psi_m(t)$ are the modulated amplitude, the RF frequency, and the modulated phase, respectively, the polarization matrix of the output light is given by

$$\begin{aligned}\begin{bmatrix} g_x(t) \\ g_y(t) \end{bmatrix} &= \sqrt{\frac{P}{2}}\,\cos\left[\alpha V_m(t)\right]e^{j[2\pi f_c t - \phi_o]}\begin{bmatrix} -j \\ 1 \end{bmatrix} \\ &\quad - \sqrt{\frac{P}{2}}\,\sin\left[\alpha V_m(t)\right] \\ &\quad \cdot e^{j[2\pi(f_c + f_{RF})t + \psi_m(t) - \phi_o]}\begin{bmatrix} +j \\ 1 \end{bmatrix}\end{aligned} \tag{3}$$

(see Appendix), where f_c and P are the optical carrier frequency and the average intensity of the input light, and ϕ_o and $\alpha$are given by (A14) and (A15), respectively. The output light is thus composed of two components: one right circularly polarized at the optical carrier frequency f_c and the other left circularly polarized at the shifted frequency $f_c + f_{RF}$. Note that the latter one is a replica of the input RF signal in the optical band, which has the same amplitude and phase as the input RF signal except for the nonlinear distortion in the amplitude, i.e., $\sin[\alpha V_m(t)]$.

The RF-to-Optic conversion scheme has the following advantages:

1) The optical signals with the same modulation formats as the RF signals are directly obtained from the RF ones without any baseband demodulation and modulation. Therefore, the RF-to-optic link conversion is easily attained. Moreover, by using optical heterodyne detection at the end of the optical link, the RF signals can be regenerated in a desired frequency band by tuning the optical frequency of the local oscillated (LO) laser.
2) In comparison with the conventional coherent optical transmission systems demonstrated in [10] and [11], where the RF signals are obtained from only a first-order sideband at the end of the optical link, the transmission performances are improved because in the conventional systems the signal power is scattered on many sidebands, while in the proposed system concentrated on one sideband [16]–[18]. We discuss this in detail in Section IV.

As for the practical aspects of the RF-to-Optic conversion scheme, this type of conversion is considered to have almost the same insertion loss and efficiency as conventional external electro-optic modulators, such as optical Mach–Zehnder intensity modulator [20], [21] and optical phase modulator [10], [11]. Furthermore, it is expected that this converter can operate at the microwave band by using traveling wave modulator like a typical $LiNbO_3$ phase modulator.

III. Coherent Fiber-Optic Microcellular Radio Communication System

In this section, we will propose the application of the RF-to-Optic conversion for the fiber-optic microcellular radio communication system. Fig. 2 shows the system configuration. We consider the high-speed radio communication systems based on B-ISDN using the millimeter-wave radio band [3], [6], which cover the microcell or picocell zone with line-of-sight transmission, and we assume that one radio carrier is used to multiplex all users in the TDMA (Time Division Multiplexed Access) format in each cell. At each base station, a radio signal is converted into an optical signal with the same modulation format using the RF-to-Optic conversion scheme to be transmitted to the central station through an optical fiber. At the central station, optical heterodyne detection regenerates

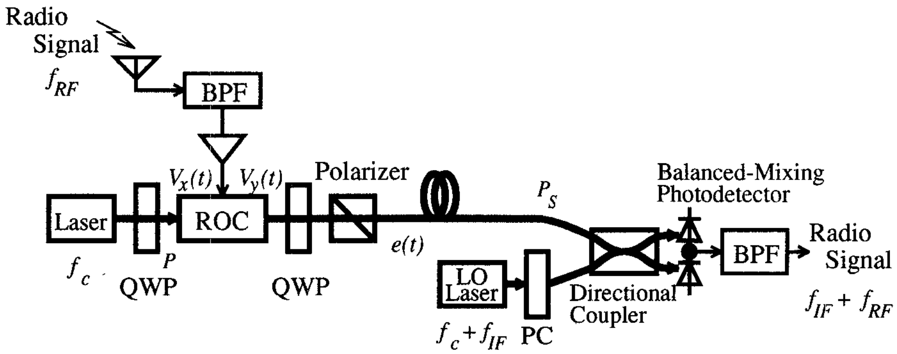

Fig. 3. Configuration of the optical link.

the RF signal, which is demodulated to get the baseband data. Since the proposed RF-to-Optic conversion scheme is applicable to various types of digital radio signal formats such as PSK, frequency shift keying (FSK) and QAM signals and so on, the base station equipment and the coherent optical link can be used flexibly for any types of radio air interfaces.

Fig. 3 shows the optical link configuration in the proposed system. Using the received radio signal and its phase-shifted signal as the orthogonal driving voltages, $V_x(t)$ and $V_y(t)$, given by (1) and (2), the output light of the RF-to-Optic converter (ROC) is composed of two circularly polarized lights as given by (3). After linearly polarizing with a quarter-wave plate (QWP) and suppressing the unmodulated optical carrier component [the first term of (3)] with a polarizer, we obtain the transmitted optical signal given by

$$e(t) = \sqrt{2P}\sin\left[\alpha V_m(t)\right]\cos\left\{2\pi(f_c+f_{RF})t+\psi_m(t)\right\} \quad (4)$$

where the constant phase, ϕ_o, is ignored. It is seen from (4) that the transmitted optical signal, $e(t)$, is a quasireplica of the radio signal. At the receiver, after matching the polarization of the received light with that of the LO light by a polarization controller (PC), the balanced-mixing-heterodyne-detection output is obtained as

$$\begin{aligned} I_{IF}(t) =& 2r\sqrt{P_S P_L}\sin\left[\alpha V_m(t)\right] \\ &\cdot\cos\left\{2\pi(f_{IF}+f_{RF})t+\psi_m(t)\right\} \end{aligned} \quad (5)$$

where P_S, P_L, f_{IF}, and r are the peak received optical signal power when $\alpha V_m(t) = \pi/2$, the LO power, the intermediate frequency (IF) and the photodetector responsivity, respectively.

In the case of binary-digital-angle-modulated signals such as FSK and PSK, since it is not necessary to keep the amplitude of the input radio signal, $V_m(t)$, through the optical transmission, we adjust the driving level, $\alpha V_m(t)$, to be $\pi/2$ to maximize the amplitude of $e(t)$ and consequently obtain the highest CNR. On the other hand, in the case of QAM signals, which are highly sensitive to the amplitude nonlinearity, $\sin[\alpha V_m(t)]$, the RF-to-Optic conversion must be operated below its saturation level.

IV. Performance of Proposed System

We evaluate the transmission performances of the proposed system by theoretical analysis and computer simulation. First, in Section IV-A, we show the CNR performances of the optical link. Next, in Section IV-B, we show the SER performances of the radio QPSK signal. Finally, in Section IV-C, we confirm the nonlinear distortion in the amplitude of the radio QAM signal and show the SER performances.

A. CNR Performance of Optical Link

Assuming that an unmodulated RF carrier is received at the base station, we compare the CNR performance of the RF-to-Optic conversion/heterodyne detection (ROC/HD) system with those of the optical phase modulation/heterodyne detection (PM/HD) system [10], [11] and the IM/DD system, theoretically.

Assuming sufficient LO power and the use of a balanced-mixing photodetector, we can ignore the signal shot and relative intensity noises [13]–[15], taking into account only the LO shot and receiver thermal noises. The CNR of the ROC/HD system is given by

$$CNR_{ROC/HD} = \frac{r^2 P_S P_L \sin^2(\alpha V_m)}{\left(erP_L + \dfrac{4kT}{R_L}\right)B} \quad (6)$$

where V_m, B, e, k, T, and R_L are the amplitude of the unmodulated RF carrier, the signal bandwidth, the electron charge, Boltzman constant, the noise temperature, and the load resistance, respectively.

For the PM/HD system with the peak received optical power P_S, the balanced-mixing-heterodyne-detection output is given by [10]

$$\begin{aligned} I_{IF\text{-}PM}(t) =& 2r\sqrt{P_S P_L} \\ &\cdot\cos\left\{2\pi f_{IF}t+\beta\cos\left[2\pi f_{RF}t+\psi_m(t)\right]\right\} \\ =& 2r\sqrt{P_S P_L}\sum_{n=-\infty}^{\infty} J_n(\beta) \\ &\cdot\cos\left\{2\pi f_{IF}t+n\left[2\pi f_{RF}t+\psi_m(t)\right]\right\} \end{aligned} \quad (7)$$

where $J_n(\beta)$ is the Bessel function and β is the phase modulation index. The first-order upper side band of $I_{IF\text{-}PM}(t)$ is the desired RF signal. Taking into account the LO shot

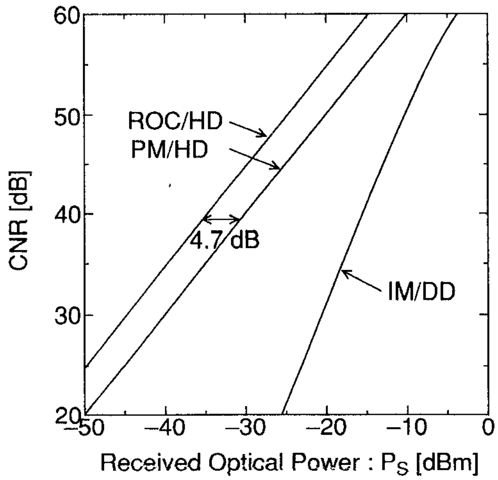

Fig. 4. The CNR performances of the optical link.

and receiver thermal noises, the CNR of the PM/HD system becomes [10]

$$CNR_{PM/HD} = \frac{r^2 P_S P_L J_1^2(\beta)}{\left(erP_L + \frac{4kT}{R_L}\right)B}. \quad (8)$$

For the IM/DD system with the intensity modulation index m and the average received optical power $P_{S.AV}$, taking into account the relative intensity, signal shot, and receiver thermal noises, the CNR is given by [5]

$$CNR_{IM/DD} = \frac{\frac{1}{2} r^2 P_{S.AV}^2 m^2}{\left(RINr^2 P_{S.AV}^2 + 2erP_{S.AV} + \frac{4kT}{R_L}\right)B}, \quad (9)$$

where RIN is the power spectral density of the relative intensity noise.

The CNR performances as functions of the received optical power, P_S, for three systems are shown in Fig. 4. In calculation, $P_{S.AV}$ of (9) is equal to P_S of (6) or (8) and parameters are tabulated in Table I. αV_m, β, and m are set to be $\pi/2$, 1.8, and 1, respectively, in order to maximize the CNR. Fig. 4 shows that the ROC/HD system remarkably improves the receiver sensitivity compared with the IM/DD system and, furthermore, has the advantage of 4.7 [dB] compared with the PM/HD system because the ROC system generates no high-order harmonics, unlike the PM system.

B. SER Performance of Radio QPSK Signal

Assuming that both radio and optical links are additive white Gaussian noise (AWGN) channels as shown in Fig. 5, we examine the SER performances of the radio QPSK signal in the proposed system by computer simulation. Furthermore, to confirm the effect of the nonlinearity of the proposed RF-to-Optic conversion scheme, we consider two kinds of RF-to-optic conversions and also examine their SER performances analytically. One is the linear system where a radio QPSK signal is supposed to be linearly converted into an optical QPSK signal. The other is the bandpass-hard-limiter system where a radio QPSK signal is passed through a bandpass-hard-limiter with the complete removal of envelope variation and without any phase distortion and converted into an optical QPSK signal. Fig. 6 illustrates the amplitude conversion characteristics of the proposed system, the linear system, and the bandpass-hard-limiter system. Note that both the linear system and the bandpass-hard-limiter system are ideal systems because the complete frequency up-conversion from RF to optic band is needed.

TABLE I
PARAMETERS USED IN FIG. 4

photodetector responsivity : r	0.8mA/mW
RIN	−150dB/Hz
LO power : P_L	10.0dBm
signal bandwidth : B	150MHz
load resistance : R_L	100Ω
noise temperature : T	300K

For the linear system, the SER of the QPSK is given by [22], [23]

$$P_{SER} = erfc\sqrt{\frac{\gamma}{2}}\left(1 - \frac{1}{4}\,erfc\sqrt{\frac{\gamma}{2}}\right), \quad (10)$$

$$\gamma = \frac{\gamma_{radio}\gamma_{opt}}{1 + \gamma_{radio} + \gamma_{opt}} \quad (11)$$

where γ_{radio} and γ_{opt} are the CNR of the radio link and the optical link, respectively.

For the bandpass-hard-limiter system, considering only AM-AM conversion, the SER of the QPSK is given by [22], [23]

$$P_{SER} = 1 - \left\{1 - \int_0^{2\pi} erfc\left(\sqrt{\frac{\gamma_{opt}}{2}}\cos\psi_m\right)p(\psi_m)\,d\psi_m\right\} \cdot \left\{1 - \int_0^{2\pi} erfc\left(\sqrt{\frac{\gamma_{opt}}{2}}\sin\psi_m\right)p(\psi_m)\,d\psi_m\right\} \quad (12)$$

where $p(\psi_m)$ is the probability density function of the phase given by [23]

$$p(\psi_m) = \frac{1}{2\pi}e^{-\gamma_{radio}}[1 + \sqrt{\pi\gamma_{radio}}\cos\psi_m \cdot \{2 - erfc(\sqrt{\gamma_{radio}}\cos\psi_m)\} \cdot e^{\gamma_{radio}\cos\psi_m}]. \quad (13)$$

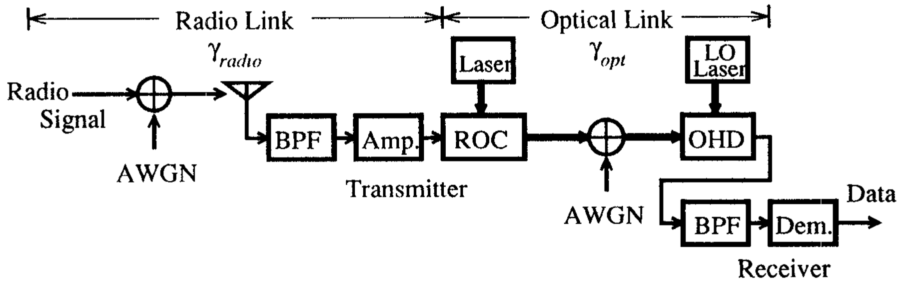

Fig. 5. Simulation model of the proposed system.

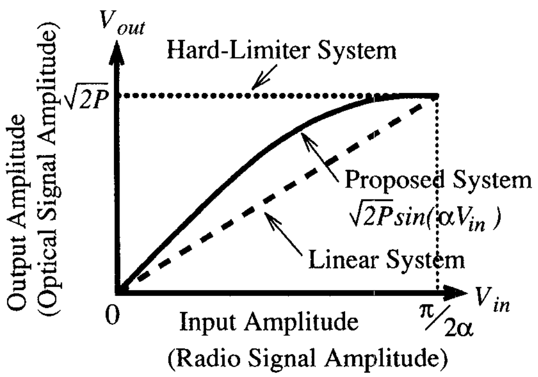

Fig. 6. Amplitude conversion characteristics.

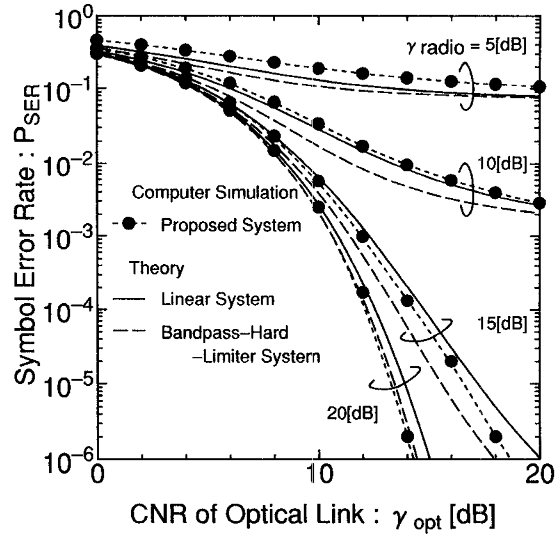

Fig. 7. The symbol error rates of the QPSK signal.

The SER's of the QPSK signal for three types of systems are shown as functions of the optical link CNR, γ_{opt}, in Fig. 7. It is seen that at low γ_{radio} the nonlinearity of the proposed conversion scheme degrades the SER slightly compared with the linear system, while at high γ_{radio} of more than 15 [dB], which is needed to obtain SER of less than 10^{-5}, the proposed system has lower SER than the linear system and attains almost the same performance as the bandpass-hard-limiter system because of the noise suppression effect due to the nonlinearity.

C. SER Performance of Radio QAM Signal

For future high-speed land-mobile communications or millimeter-wave radio subscriber loop, multilevel QAM has been intensively investigated [24], [25] because it has a high spectrum utilization efficiency under the severe constraint of bandwidth.

When a radio QAM signal is converted into an optical QAM signal by using the RF-to-Optic conversion, the amplitude nonlinearity distorts optical signal set. Since the distortion can be reduced by the backing-off from the saturated level of the electro-optic crystal, there is a tradeoff between signal quality and operating power. Assuming that both radio and optical links are AWGN channels as in the case of QPSK signals, we will examine the SER performances of the 16-ary QAM signal with a square signal constellation by computer simulation.

Fig. 8 shows simulation results of the relationship between the driving level, $\alpha V_{\max}$, and the SER of the 16-ary QAM signal under no radio link noise condition, where $V_{\max}$ is the peak amplitude of the input radio QAM signal and α is given by (A15). The peak received optical power when $\alpha V_{\max} = \pi/2$, P_S, is chosen as a parameter and the signal

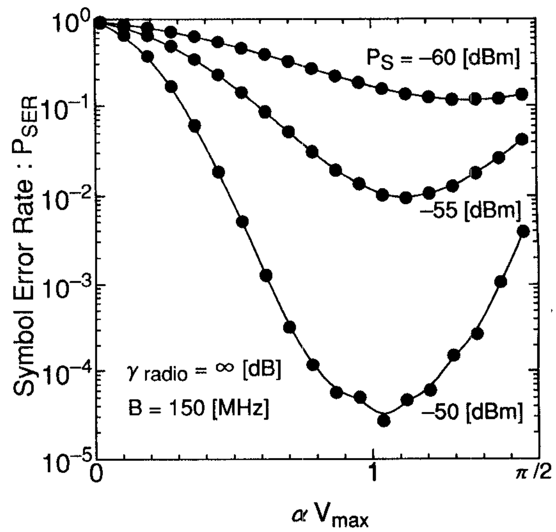

Fig. 8. Relationship between $\alpha V_{\max}$ and the symbol error rate of the 16-ary QAM signal.

bandwidth, B, is 150 MHz. It is seen from Fig. 8 that an optimum driving level, which minimizes the SER, exists and the SER is degraded as $\alpha V_{\max}$ approaches to zero or $\pi/2$ because of the power penalty resulted from the power backing-off or the nonlinear distortion.

Fig. 9 shows the SER of the 16-ary QAM signal at the optimum driving level of $\alpha V_{\max}$ indicated in Fig. 8. For

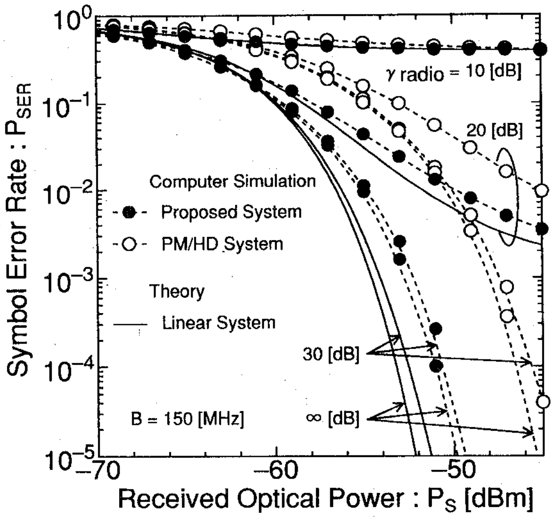

Fig. 9. The symbol error rates of the 16-ary QAM signal.

comparison, the theoretical results for the ideal linear system without any nonlinear distortion and the simulation results for the conventional PM/HD system are also shown. It is seen that at low γ_{radio} the radio link noise dominates the SER performances of all three systems. At high γ_{radio} of more than 30 dB, the receiver sensitivity of the conventional PM/HD system at $P_{SER} = 10^{-5}$ is degraded by about 7 dB compared with that of the linear system because of the power reduction due to the backing-off and the power scattering in high-order harmonics. On the other hand, the sensitivity of the proposed system is largely improved compared with that of the PM/HD system: The improvement of about 4.5 [dB] at $P_{SER} = 10^{-5}$ is obtained and this is almost the same value as in the case of an unmodulated RF carrier (see Fig. 4). Compared with the linear system, the proposed system suffers the sensitivity penalty due to the power backing-off and the generation of the unmodulated optical carrier, however the value is only about 2 [dB].

V. Conclusion

In this paper, we have proposed a new coherent fiber-optic microcellular radio communication system using a novel RF-to-Optic conversion scheme that converts an RF signal into an optical signal with the same modulation format, and we have clarified its transmission performances. The CNR performances of the optical link and the SER performances of the radio QPSK signal and the 16-ary QAM signal were shown. The following results were obtained:

1) The ROC/HD system remarkably improves the receiver sensitivity compared with the IM/DD system and, furthermore, has the sensitivity improvement of 4.7 [dB] compared with the PM/HD system.
2) At high radio CNR the SER performances of the radio QPSK signal in the proposed system is almost as same as the ideal bandpass-hard-limiter system.
3) In spite of the nonlinearity of the RF-to-Optic conversion scheme, radio QAM signals can be transmitted with higher quality than in the conventional coherent optical transmission systems.

In this paper, we have proposed a future microcellular radio network using an optical link based on coherent optical reception. From a practical viewpoint, however, we will have a number of problems to be solved for constructing the coherent optical system, such as frequency stability and spectral purity of laser, polarization control, cost, and so on. Although many of these problems are unsolved and further study is needed, in this ROC/HD system the laser phase noise will be able to be eliminated by transmitting the unmodulated optical carrier [the first term of (3)] simultaneously as a phase reference signal.

Appendix

When a light propagates along z axis through a trigonal crystal such as $LiNbO_3$, $LiTaO_3$, and so on, and electric fields, E_x and E_y, are applied along the coordinate axes x and y as shown in Fig. 1, the equation called the index ellipsoid is given by [19], [26]

$$\left(\frac{1}{n_o^2} - r_{22}E_y\right)x^2 + \left(\frac{1}{n_o^2} + r_{22}E_y\right)y^2 - 2r_{22}E_x xy = 1 \tag{A1}$$

where r_{ij} and n_o are the electrooptic coefficients and the ordinary refraction index, respectively. Moreover, in new coordinates (X, Y) rotated with respect to (x, y) by an angle θ given by

$$\theta = \frac{1}{2}\tan^{-1}\frac{E_x}{E_y} \tag{A2}$$

the index ellipsoid contains no mixed terms and is written by

$$\frac{X^2}{n_X^2} + \frac{Y^2}{n_Y^2} = 1 \tag{A3}$$

where n_X and n_Y are the refraction indices along the X and Y axes and approximately given by

$$n_X \simeq n_o\left(1 + \tfrac{1}{2}n_o^2 r_{22}\sqrt{E_x^2 + E_y^2}\right) \tag{A4}$$

and

$$n_Y \simeq n_o\left(1 - \tfrac{1}{2}n_o^2 r_{22}\sqrt{E_x^2 + E_y^2}\right) \tag{A5}$$

respectively, since in practice the variety of the refraction indices arisen from the electrooptic effect is much smaller than unity. When a light propagates through the crystal along the z axis, its two components polarized along the X and Y axes receive the phase shift of ϕ_X and ϕ_Y given by

$$\phi_X = \frac{2\pi l}{\lambda} n_X \tag{A6}$$

and

$$\phi_Y = \frac{2\pi l}{\lambda} n_Y, \tag{A7}$$

where l and λ are the crystal's length along the z axis and the wave-length of light, respectively.

The above operation on the light propagating through the electrooptic crystal is described by a polarization matrix referenced to the x and y axes given as [19]

$$\begin{bmatrix} g_x(t) \\ g_y(t) \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} e^{-j\phi X} & 0 \\ 0 & e^{-j\phi Y} \end{bmatrix} \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} f_x(t) \\ f_y(t) \end{bmatrix} \tag{A8}$$

where $f_x(t)$ and $f_y(t)$ are the input optical fields polarized along the x and y axes, and $g_x(t)$ and $g_y(t)$ are the output optical fields. If the driving voltages of the crystal along the x and y axes, $V_x(t)$ and $V_y(t)$, are mutually orthogonal RF signals, e.g., microwave or millimeter-wave signals, given by (1) and (2), θ, n_X, n_Y, ϕ_X, and ϕ_Y in (A2) and (A4)–(A7), are given as follows:

$$\theta = \pi f_{RF} t + \frac{\psi_m(t)}{2} \tag{A9}$$

$$n_X = n_o \left[1 + \frac{1}{2} n_o^2 r_{22} \frac{V_m(t)}{d}\right] \tag{A10}$$

$$n_Y = n_o \left[1 - \frac{1}{2} n_o^2 r_{22} \frac{V_m(t)}{d}\right] \tag{A11}$$

$$\phi_X = \phi_o - \alpha V_m(t) \tag{A12}$$

$$\phi_Y = \phi_o + \alpha V_m(t) \tag{A13}$$

where d is the crystal's length along the x and y axes, ϕ_o is constant phase given by

$$\phi_o = \frac{2\pi}{\lambda} n_o l \tag{A14}$$

and α is given by

$$\alpha = \frac{\pi}{\lambda} n_o^3 r_{22} \frac{l}{d}. \tag{A15}$$

We assume that an incident light to the crystal is a right circularly polarized light with a polarization matrix

$$\begin{bmatrix} f_x(t) \\ f_y(t) \end{bmatrix} = \sqrt{\frac{P}{2}} e^{j2\pi f_c t} \begin{bmatrix} -j \\ 1 \end{bmatrix} \tag{A16}$$

where f_c and P are the optical carrier frequency and the average intensity. From (A8), therefore the polarization matrix of the output light, $g_x(t)$ and $g_y(t)$, is given by (3).

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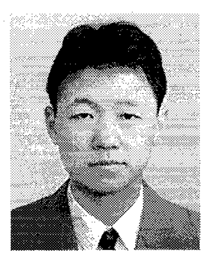

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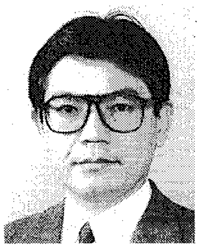

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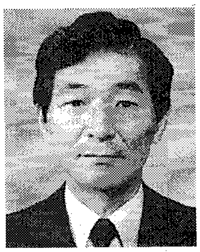

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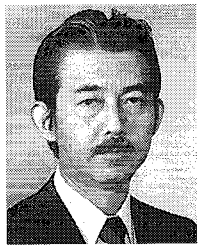

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