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Nonlinear Distortion Suppression Scheme in Optical Direct FM Radio-on-Fiber System*

Kazuo KUMAMOTO†, ***Student Member***, **Katsutoshi TSUKAMOTO**†, ***and*** **Shozo KOMAKI**†, ***Regular Members***

SUMMARY This paper proposes a nonlinear distortion suppression scheme for optical direct FM Radio-on-Fiber system. This scheme uses the interaction between the nonlinearities of DFM-LD and OFD to suppress a 3rd order intermodulation distortion. We theoretically analyze the carrier to noise-plus-distortion ratio (CNDR) and show a controlling method in the MZI type OFD to realize the proposed suppression scheme.
key words: *radio-on-fiber, SCM, DFM-LD, OFD, 3rd order intermodulation distortion*

1. Introduction

In the Radio-on-Fiber link [1]–[4] using subcarrier multiplexing (SCM) optical transmission scheme, when employing conventional optical intensity modulation/direct detection (IM/DD) system, radio signal quality is severely degraded by the combined effect of received signal level fluctuation due to multipath fading, and nonlinear intensity modulation.

On the other hand, optical FM system has been studied to improve the link gain for video transmission in the fiber-to-the-home (FTTH) [5]. Also in Radio-on-Fiber system, it has been shown that FM system is effective to reduce nonlinear distortion [6]. However, conventional SCM systems have employed SCM/FM/IM/DD method, not optical direct FM method.

In this paper, we investigate optical SCM transmission using directly frequency modulated laser diode (DFM-LD) and optical frequency discriminator (OFD) for Radio-on-Fiber Link. Some DFM SCM transmission systems have been studied [7]–[9], but only a few studies discussed the combined effect of the LD and discriminator nonlinearities [10]. However, radio signal transmission quality such as carrier to noise power ratio (CNR), carrier to distortion power ratio (CDR) and so on, has not been discussed considering both nonlinear distortion and other additive noises. As the distortion power, the 3rd order intermodulation distortion (IM3) is described, because the 2nd order intermodulation distortion is not occurred in single octave Radio-on-Fiber Link, and the 4th and higher order intermodulation are negligibly small.

This paper first examines transmission quality in the Radio-on-Fiber link using DFM-LD and OFD. Theoretical analysis of the carrier to noise-plus-distortion power ratio (CNDR) clarifies the interaction between the nonlinearities of DFM-LD and OFD. In our previous work, we have improved CNDR by setting optimum FSR of OFD according to nonlinearity of DFM-LD [11], [12]. However, it is difficult to setting optimum FSR value. As the practical scheme, we newly proposed IM3 suppression scheme by shifting transmission characteristics of the mach-zehnder interferometer (MZI) for carrier frequency by using a phase shifter. Proposed scheme can achieve easily control of optimum OFD nonlinearity.

In Sect. 2, we describe a system configuration of the Radio-on-Fiber Link using DFM-LD and OFD, and introduce analytical models for the nonlinearity in DFM-LD and OFD. Then the IM3 is theoretically derived. In Sect. 3, we theoretically analyze the CNDR considering the interaction between the nonlinearities of DFM-LD and OFD. Finally, in Sect. 4, we propose the control scheme for optical direct FM Radio-on-Fiber system to setting optimum OFD transmission characteristics.

2. Radio-on-Fiber Link Using DFM-LD and OFD

Figure 1 illustrates the configuration of the Radio-on-Fiber Link using DFM-LD and OFD. A radio base station (RBS) receives multicarrier radio signals and di-

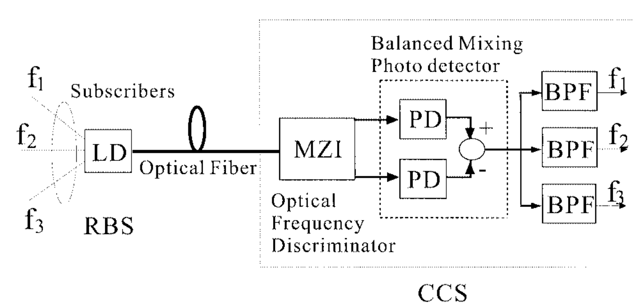

Fig. 1 Configuration of radio-on-fiber link using directly optical FM and OFD.

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†The authors are with the Department of Communications Engineering, Faculty of Engineering, Osaka University, Suita-shi, 565-0871 Japan.

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Table 1 FM characteristics of LD.

	LD1	LD2
1st coefficiency α [MHz/mA]	72	65
2nd coefficiency β	0.3	0.01
3rd coefficiency γ	2.0×10^{-3}	-3.0×10^{-5}

rectly frequency modulates LD with the radio signal used as a driving current. The current, i_{in}, can be represented as

$$i_{in}(t) = \sum_{k=1}^{K} R_k(t) \cos 2\pi f_k t \tag{1}$$

where $R_k(t)$ and f_k are the envelope and frequency of the kth radio signal, respectively. The LD has the nonlinearity in its frequency modulation characteristic. We represent the nonlinearity of the DFM-LD by Taylor expansion as

$$f_m(t) = \alpha i_{in}(t) + \beta i_{in}^2(t) + \gamma i_{in}^3(t) \tag{2}$$

where $f_m(t)$ is the freqency shift and the first, second and third coefficients, α, β and γ, are calculated from the frequency modulation efficiency of the LD, which are given by the measured value of actual LD. In this paper, we use FM characteristic of two types of LD shown in Table 1 [13].

When the SCM signal, $i_{in}(t)$, directly frequency-modulates the LD, the optical FM signal from the LD is written by

$$\begin{aligned} s(t) \;=\; & \sqrt{2P_t(1+y(t))} \\ & \times \cos\left[2\pi\left(f_c t + \int_{-\infty}^{t} f_m(t)dt\right) + \phi_s(t)\right] \end{aligned} \tag{3}$$

where P_t is the optical transmitting power, f_c is the optical carrier frequency, $f_m(t)$ is given by Eq. (2), and $\phi_s(t)$ is the LD phase noise. $y(t)$ is the parasitic intensity modulation component, which is represented by

$$y(t) = \alpha_{IM} i_{in}(t) \tag{4}$$

where α_{IM} is the intensity modulation efficiency.

After transmission over fiber, the optical FM signal is converted into optical IM signal at OFD using Mach-Zehnder Interferometer (MZI). The transmissions of two output-ports of the MZI type OFD, $T_1(f)$ and $T_2(f)$, are given by

$$T_n(f) = \frac{1}{2}\left[1 \mp \cos\left(\pi \frac{f}{\mathrm{FSR}}\right)\right] : \quad n = 1, 2 \tag{5}$$

where FSR is the free spectral range as shown in Fig. 2. Then, the optical intensity of the two port outputs of the OFD are given by

$$\begin{aligned} P_{o-n}(t) = P_r & \left[1 + \frac{y(t)+y(t-\tau)}{2}\right] \\ & \times T_n(f_c + f_m(t) + c(t)) : \quad n = 1, 2 \end{aligned} \tag{6}$$

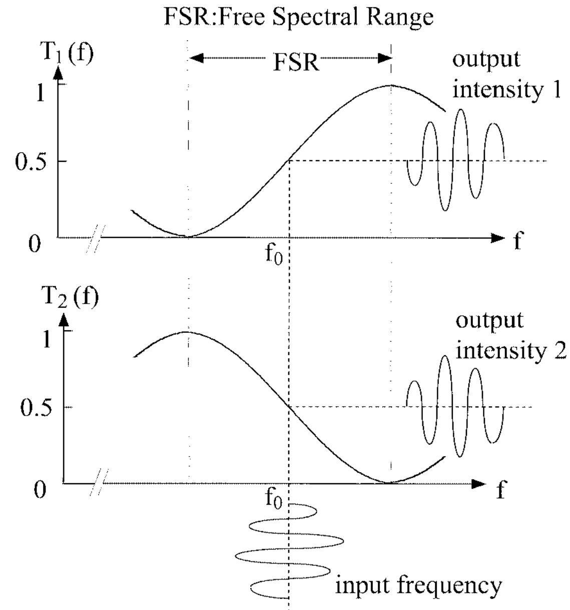

Fig. 2 Mach-Zehnder Interferomerter (MZI) type optical frequency discriminator.

where P_r is the received optical power, $c(t)$ is the white optical frequency noise, and τ is the time delay in OFD. Here, assuming the small frequency deviation, the discriminator transmission can be expanded in Taylor series [7]:

$$\begin{aligned} T_n(f) = & T_n^{(0)} + T_n^{(1)}(f - f_0) \\ & + \frac{1}{2} T_n^{(2)}(f - f_0)^2 + \cdots \quad (n = 1, 2) \end{aligned} \tag{7}$$

and

$$T_1(f)^{(j)} \,\big|_{f_0} = -T_2(f)^{(j)} \,\big|_{f_0} \quad (j = 1, 2, \cdots) \tag{8}$$

where $T_n^{(j)}$ is j-th coefficient of Taylor series and f_0 is the operating point of the MZI. It is seen from Eqs. (6)–(8) that the MZI type OFD causes a phase difference of π between the intensity signal components of $P_{o-1}(t)$ and $P_{o-2}(t)$. Therefore, we can use the balanced mixing photodetector (BMPD) to direct-detect these signals. Assuming perfectly balanced discriminator and identical photodetectors, then the detector output current is written by

$$\begin{aligned} i_{out}(t) = & rP_r \left[2T_1^{(1)}\alpha + \alpha_{IM}(T_1^{(0)} - T_2^{(0)})\right] i_{in}(t) \\ & + 2rP_r \left[T_1^{(1)}\beta + \frac{1}{2}T_1^{(2)}\alpha^2 + \alpha_{IM} T_1^{(1)}\alpha\right] i_{in}^2(t) \\ & + 2rP_r \left[T_1^{(1)}\gamma + T_1^{(2)}\alpha\beta + \frac{1}{6}T_1^{(3)}\alpha^3 \right. \\ & \left. + \alpha_{IM}\left\{T_1^{(1)}\beta + \frac{1}{2}T_1^{(2)}\alpha^2\right\}\right] i_{in}^3(t) + n(t) \end{aligned} \tag{9}$$

where r is the responsivity of PD, $n(t)$ is the additive noise current including the signal shot noise, the receiver thermal noise, and the additive intensity noise caused by the laser phase noise at the discriminator, which is given by

$$n_{phase}(t) = 2rP_rT_1^{(1)}c(t). \tag{10}$$

The first term of $i_{out}(t)$ is the demodulated SCM radio signal, and it is seen from Eq. (9) that the balanced mixing detection improves the signal power by 3 dB. The 2nd, and 3rd terms are the higher order distortion due to the nonlinearities of both LD and the discriminator. The parasitic intensity modulation component also causes the 3rd order distortion as shown in the 3rd term of $i_{out}(t)$, the distortion which is caused by the multiplication between the parasitic intensity modulation component and the signal intensity converted from optical frequency at the discriminator. In the next section, we theoretically analyze the CNDR based on the Eqs. (9) and (10).

3. Theoretical CNDR Analysis

Assuming single octave and three channel SCM radio signal in Eq. (1), we theoretically analyze the noise power, N, and the distortion power, D. The IM2 is not occurred in single octave channel and 4th and higher order distortion power are negligible small. So we can consider the distortion power, D, is equal to the IM3 power. The N and D normalized by carrier power, C, are respectively derived as

$$\left(\frac{N}{C}\right) = \frac{qB}{rP_r(T_1^{(1)})^2\Delta f^2} + \frac{4kT}{(rP_r)^2(T_1^{(1)})^2\Delta f^2 R_L} + \frac{2\Delta\nu B}{\pi\Delta f^2} \tag{11}$$

and

$$\left(\frac{D}{C}\right) = \frac{9}{4}\left[\frac{T_1^{(1)}\gamma + T_1^{(2)}\alpha\beta + \frac{1}{6}T_1^{(3)}\alpha^3}{(T_1^{(1)})^2} + \frac{\alpha_{IM}\alpha\beta}{2T_1^{(1)}} + \frac{T_1^{(2)}\alpha_{IM}\alpha^3}{4(T_1^{(1)})^2}\right] \tag{12}$$

where Δf is the maximum frequency deviation which is defined by αR_2, R_2 is the envelope of SCM radio signal, q is electron charge, B is the bandwidth per a carrier, k is Boltzman constant, T is noise temperature, R_L is the load resistance, and $\Delta\nu$ is the full width half maximum (FWHM) of LD spectral line width.

Assuming that we set the optical carrier frequency f_c to be the operating point f_0 at the half transmission of the frequency discriminator, we theoretically analyze the noise power, N, and the IM3 power, D. From Eqs. (11) and (12) the N and D normalized by carrier power, C, are respectively given by

$$\left(\frac{N}{C}\right) = \frac{4qB}{rP_r\pi^2\left(\frac{\Delta f}{\mathrm{FSR}}\right)^2} + \frac{16kTB/R_L}{(rP_r)^2\pi^2\left(\frac{\Delta f}{\mathrm{FSR}}\right)^2} + \frac{\Delta\nu B}{\pi\Delta f^2} \tag{13}$$

and

$$\left(\frac{D}{C}\right) = \frac{9}{4}\left[\frac{\gamma}{\alpha^3} - \frac{1}{6}\frac{\pi^2}{\mathrm{FSR}^2} + \frac{\alpha_{IM}\beta}{\alpha^3}\right]^2 \Delta f^4 \tag{14}$$

Consequently, the CNDR is given by

$$\left(\frac{C}{N+D}\right) = \left[\left(\frac{N}{C}\right) + \left(\frac{D}{C}\right)\right]^{-1} \tag{15}$$

It is seen from Eq. (13) that the shot and thermal noise power decrease in proportion to the Δf^2 or in proportion to the inverse square of FSR, and the additive noise power due to the LD phase noise (third term of Eq. (13)) also decreases in proportion to the Δf^2. On the contrary, the IM3 power D increases in proportion to the Δf^4 or $1/(-\mathrm{FSR}^2 + \mathrm{FSR}^4)$.

Equations (13)–(15) show that the additive noise dominates the CNDR when the value of Δf is small, while IM3 is dominant when Δf is relatively large. So we can find an optimum Δf to maximize CNDR. Figure 3 shows the numerical results of CNDR in the case of FSR of 4 and 15 [GHz] for different values of the LD spectral linewidth $\Delta\nu$. The parameters used in calculation are shown in Table 2. It is found from Fig. 3

Table 2 Parameters used in calculation.

Carrier number (N)	3
Bandwidth per radio carrier (B)	300 [kHz]
Received optical power (P_r)	−10 [dBm]
PD responsivity (r)	0.8 [mA/mW]
Noise temperature (T)	300 [K]
Load resistance (R_L)	50 [Ω]
Intensity modulation efficiency (α_{IM})	0.01

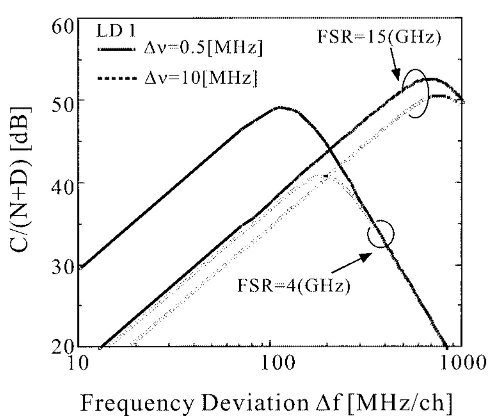

Fig. 3 $C/(N+D)$ versus frequency deviation Δf.

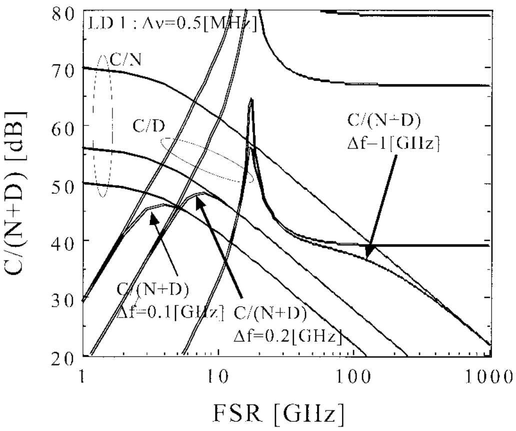

Fig. 4 Relationship between $C/(N+D)$ and FSR.

that the LD phase noise deteriorate CNDR, and in the case of large FSR (15 GHz), its penalty in CNDR is decreased because the frequency sensitivity of the discriminator decreases as FSR increases. However, the power decrease in signal intensity converted from FM component results in C/N degradation. Although the phase noise should be suppressed in FM system, however, we can find the maximum CNDR is improved when FSR is 15 GHz. It is seen from Eq. (14) that C/N is greatly improved when amplitude of IM3 component becomes very small. Therefore, we can find the value of FSR to improve C/D according to the parameters α, β and γ in LD frequency modulation characteristic. In the next section, we will discuss about this IM3 suppression effect in more detail.

Figure 4 shows the relationship between CNDR and FSR of optical discriminator for different values of the frequency deviation, Δf. We can find an optimum value of FSR to maximize CNDR. When free spectral range, FSR, is relatively small, IM3 is a dominant noise source, and CNDR is improved mainly due to decreasing IM3. In constant, when FSR is relative large, C/N dominates CNDR, and CNDR decreases as the value of FSR is greater. In the case of Δf=1 GHz, however, CNDR is dominated only by C/D in the almost all range of FSR and the maximum value of CNDR is the value of C/N in the case of IM3 distortion is negligible small. This suppression effect of IM3 power is caused by the interaction between LD and discriminator nonlinearities as shown in Eq. (14). The value of FSR_0 to suppress IM3, is analytically derived as

$$\mathrm{FSR}_0 = \frac{\pi\alpha^{\frac{3}{2}}}{\sqrt{6(\gamma + \alpha_{\mathrm{IM}}\beta)}} \tag{16}$$

In this way, we can suppress IM3 ideally by using adequate FSR value when LD frequency modulation characteristic, α, β and γ, are not fluctuated. When α, β and γ have time fluctuation, however, the strict control of LD should be required to suppress their fluctuation at the transmitter. Therefore, LD equipment

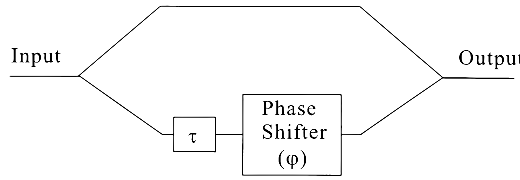

Fig. 5 Nonlinearity suppression scheme at MZI.

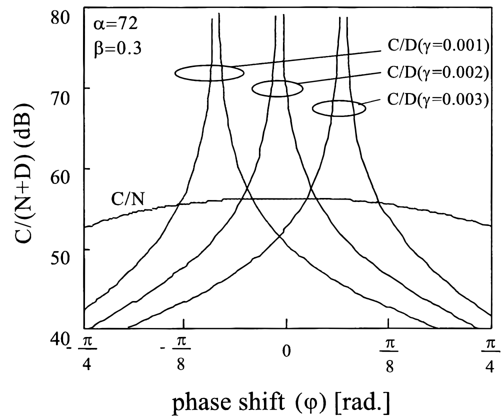

Fig. 6 Relationship between C/N, C/D and phase shift, φ, for different values of parameter γ.

becomes very complicated. On the other hand, we can cope with time fluctuation of LD frequency modulation characteristic at the receiver, because the transmission characteristic of the OFD, that is, the nonlinearity, can be controlled more easily. So, in the next section, we discuss the IM3 suppression method by controlling the OFD transmission characteristic.

4. Control of the OFD Transmission Characteristics

It is difficult to control FSR of MZI to suppress the IM3 distortion. As the practical method, we newly propose the controlling scheme by shifting OFD transmission characteristics for a carrier frequency. In Fig. 5, we illustrate a OFD as a post-detection circuit [14]. The insertion of phase shifter on the lower blanch of MZI can shift the transmission characteristic of the MZI [15]. Although it causes penalty of C/N, it does not cause any penalty of C/D. In this section, we theoretically analyze the C/N and C/D in the case of using phase shifter.

By inserting phase shifter, transmission given by Eq. (5) becomes

$$T_n(f) = \frac{1}{2}\left[1 \mp \cos\left(\pi\frac{f}{\mathrm{FSR}} + \varphi\right)\right] : \quad n = 1, 2 \tag{17}$$

where φ is the phase shift of the phase shifter.

Figure 6 shows the C/N and C/D versus the phase shift, φ, in the case of γ changing from 0.001 to 0.003. Δf and FSR are fixed to be 1 GHz and 17 GHz, respectively. Figure 7 also shows the C/N and C/D versus

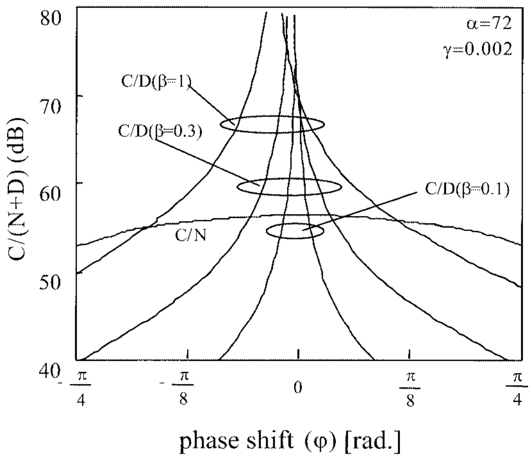

Fig. 7 Relationship between C/N, C/D and phase shift, φ, for different values of parameter β.

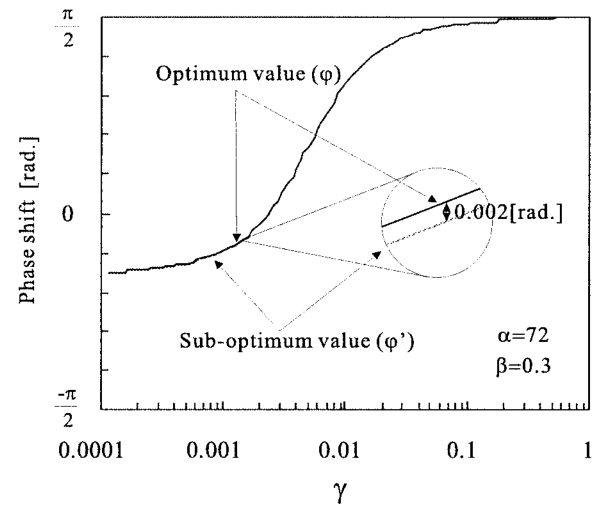

Fig. 8 The sub-optimum phase shift, φ', for different values of γ.

the phase shift, φ, in the case of β changing from 0.1 to 1. It is found from Fig. 6 that the optimum phase shift, φ, largely changes according to the changing of γ. On the other hand, it is found from Fig. 7 that the optimum phase shift, φ, hardly changes for the changing of β. In these figures, C/N is deteriorated by phase shift. Because MZI can not be operated at half transmission point and two port outputs of OFD becomes different power. Thus balanced detection gain is deteriorated less than 3 dB and it becomes C/N penalty. The penalty of C/N, CN_{Loss} is derived as

$$CN_{Loss} = (\cos^2\varphi)^{-1}. \tag{18}$$

For example, C/N penalty of 3 dB is caused when $\varphi = \pi/4$.

On the other hand, C/D is not deteriorated by phase shift, because IM3 power, D, is decreased at same ratio with carrier power, and we can apply Eq. (12) without any revision.

As mentioned above, control of the transmission characteristics is effective to improve C/D and CNDR. However, it is very difficult to find an optimum value of φ for arbitrary set of α, β and γ. Thus we derive the sub-optimum phase shift, φ', from the 1st term of Eq. (12) which dominates IM3 distortion, D, because we assume intensity modulation efficiency, α_{IM} is relatively small. This term is

$$\begin{aligned} f(\varphi') &= T_1^{(1)}\gamma + T_1^{(2)}\alpha\beta + \frac{1}{6}T_1^{(3)}\alpha^3 \\ &= \frac{1}{2}\frac{\pi}{\mathrm{FSR}}\sqrt{\left(\gamma - \frac{1}{6}\left(\frac{\pi}{\mathrm{FSR}}\right)^2\alpha^3\right)^2 + \left(\frac{\pi}{\mathrm{FSR}}\alpha\beta\right)^2} \\ &\quad \times \sin\left(\frac{\pi}{\mathrm{FSR}}f_c + \phi + \varphi'\right) \end{aligned} \tag{19}$$

where ϕ is given by

$$\phi = \tan^{-1}\left(\frac{\dfrac{\pi}{\mathrm{FSR}}\alpha\beta}{\gamma - \dfrac{1}{6}\left(\dfrac{\pi}{\mathrm{FSR}}\right)^2\alpha^3}\right) \tag{20}$$

Setting $f(\varphi') = 0$, we can find the sub-optimum phase shift, φ', as

$$\varphi' = n\pi - \frac{\pi}{\mathrm{FSR}}f_c - \phi : \quad n = \text{integer}. \tag{21}$$

Figure 8 shows the optimum phase shift, φ, and sub-optimum phase shift, φ', for different values of γ. It is found from this figure that we can obtain an optimum and a sub-optimum phase shift in the range of $(-\pi/2, \pi/2)$ uniquely and both phase shift are nearly equal. Thus Eq. (21) is suitable to suppress IM3 distortion.

5. Conclusions

In this paper, we have proposed a nonlinear distortion suppression scheme using the interaction between the nonlinearities of DFM-LD and OFD. We have newly proposed the control scheme of the MZI transmission characteristics to suppress IM3 distortion. Proposed scheme can suppress IM3 power effectively, and theoretical analysis has shown the improvement in the CNDR.

As the father study, we will investigate the effective of the proposed scheme for the IM2 suppression, which causes in a multi octave transmission like a CATV system.

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Kazuo Kumamoto was born in Hiroshima, Japan in February 17, 1976. He received the B.E. and M.E. degrees in Communications Engineering from Osaka University, Osaka, Japan, in 1998 and 1999 respectively. He is currently pursuing the Ph.D. degree at Osaka University. He is engaging in the research on radio and optical communication systems.

Katsutoshi Tsukamoto was born in Shiga, Japan in October 7, 1959. He received the B.E., M.E. and Ph.D. degrees in Communications Engineering from Osaka University, in 1982, 1984 and 1995 respectively. He is currently an Associate Professor in the Department of Communications Engineering at Osaka University, engaging in the research on radio and optical communication systems. He is a member of IEEE and ITE. He was awarded the Paper Award of IEICE, Japan in 1996.

Shozo Komaki was born in Osaka, Japan in 1947. He received B.E., M.E. and Ph.D. degrees in Communications Engineering from Osaka University, Osaka, Japan, in 1970, 1972 and 1983 respectively. In 1972, he joined the NTT Radio Communication Labs., where he has engaged in repeater development for a 20-GHz digital radio system, 16-QAM and 256-QAM systems. From 1990, he moved to Osaka University, Faculty of Engineering, and engaging in the research on radio and optical communication systems. He is currently a Professor of Osaka University. Dr. Komaki is a senior member of IEEE, and a member of the Institute of Television Engineering of Japan (ITE). He was awarded the Paper Award and the Achievement Award of IEICE, Japan in 1977 and 1994 respectively.