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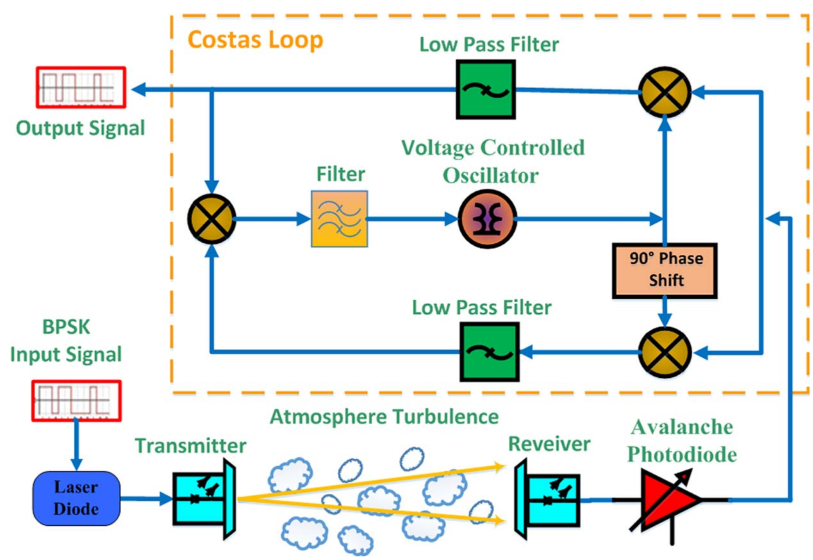

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Investigation of Costas Loop Synchronization Effect on BER Performance of Space Uplink Optical Communication System With BPSK Scheme

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Abstract: The Costas loop is the key technique of synchronous demodulation in the next generation of satellite optical communication systems. To better understand the Costas loop, the relationship between phase deviation of the Costas loop and bit error rate (BER) performance of a binary-phase-shift keying (BPSK) space uplink optical communication system is achieved. Furthermore, the BER performance versus frequency deviation, zenith angle, data rate, and divergence angle are analyzed. Simulation results indicate that BER performances are not sensitive for parameters when the phase deviation of the Costas loop is designed with restriction of $\pi/16$. These results are helpful for enhancing BER performance and the design of space optical communication systems.

Index Terms: Costas loop, coherent communications, free-space optical communication, phase modulation, atmospheric turbulence.

1. Introduction

With the increase of data rate requirement, coherent communication has attracted more attention as the preferred technique for the next generation of satellite optical communication systems because of better performance of bit error rate (BER) [1]–[3]. The Costas loop is used to produce a local oscillation the same with carrier wave for coherent demodulation in carrier synchronization system [4]. It is agreed by practical experience that the Costas loop owns better tolerance of laser phase noise and provides excellent performance at high modulation rate [5]–[7]. Thus, it is commonly applied into coherent communication system.

During the transmission process in the uplink optical communication system, people usually attract attention to analyzing how atmospheric turbulence affects the transmission signal [8], [9]. The effect of atmospheric turbulence includes intensity scintillation, beam wander and phase fluctuation towards transmission signal [10], [11]. Apart from transmission process, the part of coherent demodulation in receiving terminal also influences the system. The Costas loop, which will be discussed here, inevitably plays a role in the whole performance of the system [12]–[15]. However, the effect of the Costas loop on space optical communication system with atmospheric turbulence has never been researched before.

For the process of coherent demodulation, the reproduced carrier wave in receiving terminal is utilized to interact with the receiving signal. Theoretically, the reproduced carrier wave should be the same as that modulated with initial transmission signal for the best performance of system. However, for the Costas loop practical system, the carrier wave reproduced by voltage-controlled oscillator (VCO) obtains the phase deviation [16]. Thus, this phase deviation of the Costas loop inevitably decreases the signal quality in the demodulation process [17].

In the practical experiment of space optical communication, the modulation scheme of binary phase-shift keying (BPSK) is widely applied [18], [19]. Thus, we also use this scheme here. As the BER is the most important parameter to measure the transmission quality, we analyze the effect of the Costas loop on the BER performance in space optical communication system under atmospheric turbulence. In the research process, intensity scintillation, beam wander and phase fluctuation caused by atmospheric turbulence have all been considered. Based on atmospheric turbulence model mentioned above, we further analyze the effect of the Costas loop for the practical parameters. We hypothesize five representative phase deviations $(0, \pi/32, \pi/16, \pi/8, 3\pi/16, \pi/4)$ caused by the Costas loop to show the performance of the Costas loop in different level of conditions. Under different Costas phase deviations, the performances of BER versus frequency deviation, zenith angle, divergence angle and data rate are analyzed. These analyses are beneficial to the enhancement of the BER performance and the practical design of system in space optical communication.

2. Theory Model

In order to research the Costas loop synchronization effect on the coherent demodulation, it is necessary to comprehend whole transmission process. The whole communication model includes transmitting terminal system, atmosphere propagation and receiving terminal system. When the input signal is modulated into carrier wave from laser diode, it is sent through atmospheric turbulence. During the propagation process, both the intensity and phase of optical signal will be affected by atmospheric turbulence. For the effect of atmospheric turbulence on optical signal intensity in space uplink optical communication system, it includes the beam wander and intensity scintillation. To be more specific, the beam center deviates random distance away from the receiving point affected by the beam wander and the optical signal shows irregular intensity variation caused by intensity scintillation. Meanwhile, the phase of optical signal also shifts irregularly caused by the phase fluctuation from atmospheric turbulence. At the receiving terminal, after the optical signal has transmitted through atmospheric channel, it will be amplified in the avalanche photodiode. Then, the amplified signal is further taken to the Costas loop system. Demodulating with reproduced carrier wave from voltage-controlled oscillator, initial digital signal is obtained. The whole process is shown as block diagram in Fig. 1.

As the signal is modulated by BPSK, the transmission signal can be shown [20] as

$$y(t) = A\cos(\omega_c t + \varphi) \tag{1}$$

where A is intensity of wave form, ω_c is the frequency of the wave, and φ is the absolute phase of wave form, which means the transmission information. As it is based on the BPSK scheme, it shows that when the digital information 1 is transmitted, φ shows 0 and when digital information 0 is transmitted, φ shows π. Then, (1) can be calculated by [20]

$$y(t) = \begin{cases} A\cos\omega_c t, & 1 \text{ is transmitted} \\ -A\cos\omega_c t, & 0 \text{ is transmitted.} \end{cases} \tag{2}$$

It is agreed that the phase of the modulated signal is affected by atmospheric turbulence. The phase deviation $\Delta\psi$ caused by atmospheric turbulence is added into initial signal. Furthermore,

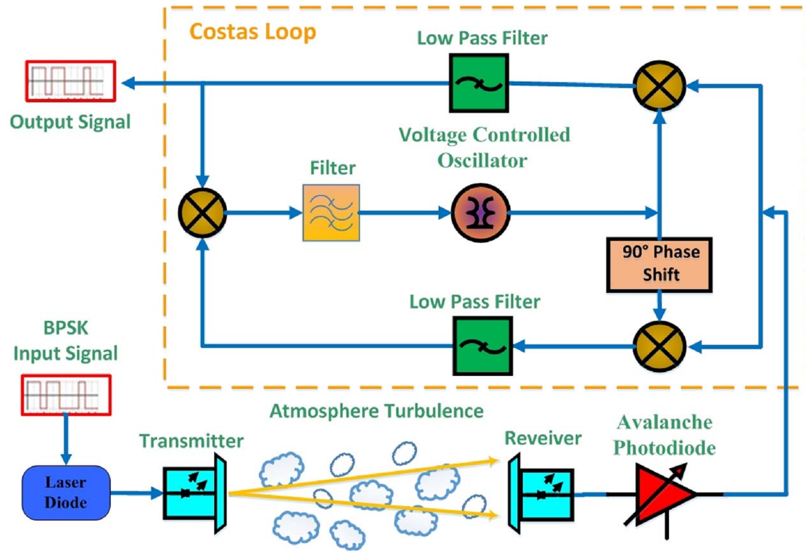

Fig. 1. Diagram of process of transmitting and receiving on the Costas loop.

there exists normal Gaussian noise $n(t)$ in the process. Thus, the receiving signal is

$$y(t) = \begin{cases} a\cos(\omega_c t + \Delta\psi) + n(t), & 1 \text{ is transmitted} \\ -a\cos(\omega_c t + \Delta\psi) + n(t), & 0 \text{ is transmitted} \end{cases} \tag{3}$$

where $a = AK$ is intensity of receiving signal, and K is the transmission coefficient. $n(t)$ is the addictive noise from channel. $\Delta\psi$ is the phase deviation caused by atmospheric turbulence effect and follows Gauss distribution. If $n(t)$ is taken the method of orthogonal decomposition from [20], the signal is illustrated by

$$y(t) = \begin{cases} [a + n_c(t)]\cos(\omega_c t + \Delta\psi) - n_s(t)\sin(\omega_c t + \Delta\psi), & 1 \text{ is transmitted} \\ [-a + n_c(t)]\cos(\omega_c t + \Delta\psi) - n_s(t)\sin(\omega_c t + \Delta\psi), & 0 \text{ is transmitted} \end{cases} \tag{4}$$

where $n_s(t)$ and $n_c(t)$ are component product of addictive noise, and they are all follow Gauss distribution. The mean value is 0, and variation is σ_n^2 [20].

On the other hand, according to the coherent demodulation technique in carrier synchronization system, Costas loop is applied to reproduce carrier wave. The output voltage illustrates the extracted carrier wave, which is shown as [21]

$$v_g = \cos(\omega_c t + \varphi') \tag{5}$$

where ω_c is the frequency of carrier wave, and φ' is the phase by the Costas loop.

Based on signal expression in (5), if the digital information 1 is transmitted, the phase φ is 0. There exists phase deviation $\Delta\varphi$ caused by the Costas loop compared with initial phase φ. Thus the φ' in (5) can be given by [21]

$$\varphi' = 0 + \Delta\varphi \tag{6}$$

where $\Delta\varphi$ is the phase deviation caused by the Costas loop circuit. In this process, the feedback voltage of the Costas loop dominates the frequency of voltage-controlled oscillator. The v_g controls the phase at the least level. Thus, v_g is the local carrier wave of demodulation in the receiving terminal. Then, v_g in (5) is shown as [21]

$$v_g = \cos(\omega t + \Delta\varphi). \tag{7}$$

During the coherent demodulation process in the Costas loop, the demodulated signal $x(t)$ is calculated by the product of receiving signal $y(t)$ and carrier wave $v_g(t)$, which is shown as

$$x(t) = \{[a + n_c(t)]\cos(\omega_c t + \Delta\psi) - n_s(t)\sin(\omega_c t + \Delta\psi)\}\cos(\omega_c t + \Delta\varphi). \quad (8)$$

After simplification and passing by low-pass filter, it is

$$x(t) = \frac{1}{2}[a + n_c(t)]\cos(\Delta\varphi - \Delta\psi) + \frac{1}{2}n_s(t)\sin(\Delta\varphi - \Delta\psi). \quad (9)$$

We can identify the overall phase deviation κ from both atmospheric turbulence and the Costas loop by

$$\kappa = \Delta\varphi - \Delta\psi. \quad (10)$$

Thus, the receiving signal is

$$x(t) = \frac{1}{2}[a + n_c(t)]\cos(\kappa) + \frac{1}{2}n_s(t)\sin(\kappa). \quad (11)$$

The $\Delta\psi$ is caused by the atmospheric turbulence, and it is followed Gauss distribution [10]. Besides, $\Delta\varphi$ is a constant in the Costas loop. Thus, the identified overall phase deviation κ follows the Gauss distribution and probability density distribution is calculated by

$$f(\kappa) = \frac{1}{\sqrt{2\pi}\sigma_\kappa \exp\left(-\frac{(\kappa-\Delta\varphi)^2}{2\sigma^2{}_\kappa}\right)} \quad (12)$$

where $\sigma_k^2 = 2\pi\Delta f_{IF}/f_s$ is variation of κ, Δf_{IF} is the statistical standard frequency deviation, $f_s = 1/T_s$ is the transmission frequency, and T_s is the time duration per bit.

As $n_s(t)$ and $n_c(t)$ are followed Gauss distribution, $x(t)$ follows the Gaussian distribution [10]. The mean value and variation are calculated by

$$m_1 = \frac{1}{2}a\cos(\kappa) \quad (13)$$

$$\sigma_1 = \frac{1}{4}\sigma_n^2. \quad (14)$$

Simultaneously, when the digital information 0 is transmitted, the receiving signal $x(t)$ follows Gauss distribution. The mean value and variation are

$$m_0 = -\frac{1}{2}a\cos(\kappa) \quad (15)$$

$$\sigma_0 = \frac{1}{4}\sigma_n^2. \quad (16)$$

Thus, the probability density functions for different digital information are

$$f_1(x) = \frac{1}{\sqrt{2\pi}\left(\frac{1}{2}\sigma_n\right)}\exp\left\{\frac{-\left(x - \frac{1}{2}a\cos\kappa\right)^2}{2\cdot\frac{1}{4}\sigma_n^2}\right\} \quad (17)$$

$$f_0(x) = \frac{1}{\sqrt{2\pi}\left(\frac{1}{2}\sigma_n\right)}\exp\left\{\frac{-\left(x + \frac{1}{2}a\cos\kappa\right)^2}{2\cdot\frac{1}{4}\sigma_n^2}\right\}. \quad (18)$$

During transmission process, if the digital information 1 is transmitted, but it is demodulated as 0 in receiving terminal, the BER is shown as

$$P\left(\frac{0}{1}\right) = \int_{-\infty}^{0}\frac{1}{\sqrt{2\pi}\left(\frac{1}{2}\sigma_n\right)}exp\frac{-\left(x - \frac{1}{2}a\cos\kappa\right)^2}{2\left(\frac{1}{2}\sigma_n\right)^2}dx. \quad (19)$$

It can be simplified by

$$P\left(\frac{0}{1}\right)=\frac{1}{2}\operatorname{erfc}\left(\frac{\frac{1}{2}a\cos\kappa}{\sqrt{2}\left(\frac{1}{2}\sigma_n\right)}\right)=\frac{1}{2}\operatorname{erfc}\left(\frac{a\cos\kappa}{\sqrt{2}\sigma_n}\right). \tag{20}$$

If the digital information 0 is transmitted, but it is demodulated as 1 in receiving terminal, the BER is shown as

$$P\left(\frac{1}{0}\right)=\int_0^\infty\frac{1}{\sqrt{2\pi}\left(\frac{1}{2}\sigma_n\right)}\exp\frac{-\left(x+\frac{1}{2}a\cos\kappa\right)^2}{2\left(\frac{1}{2}\sigma_n\right)^2}dx. \tag{21}$$

It is also simplified by

$$P\left(\frac{1}{0}\right)=\frac{1}{2}\operatorname{erfc}\left(\frac{a\cos\kappa}{\sqrt{2}\sigma_n}\right). \tag{22}$$

Thus, when the different signal is transmitted with equal probability, the overall BER is

$$\mathrm{BER}=\frac{1}{2}P\left(\frac{1}{0}\right)+\frac{1}{2}P\left(\frac{0}{1}\right)=\frac{1}{2}\operatorname{erfc}\left(\frac{a\cos\kappa}{\sqrt{2}\sigma_n}\right). \tag{23}$$

In research process, the avalanche photodiode (APD) is utilized as the detector to amplify the receiving signal. Thus the mean value a and variance of noise σ_n^2 can be expressed as [21]

$$a=G\cdot e\cdot(K_s+K_b)+I_{dc}T_s \tag{24}$$

$$\sigma_n^2=(G\cdot e)^2\cdot F\cdot(K_s+K_b)+\sigma_T^2 \tag{25}$$

where G is gain factor, e is electron quantity, $K_b=\eta I_b T_s/hv$ is the photon count of the background light, η is quantum efficiency, I_b is the background light in the optical communication system, I_{dc} is dark current, T_s is time duration per bit, v is the frequency of the signal light, h is the Planck constant, F is the additional noise factor, K_s is the photon count corresponding to the receiving intensity, $\sigma_T^2=2\kappa_c TT_s/R_L$ is thermal noise, k_c is Boltzmann constant, T is the temperature, and R_L is load resistance, and the specific values can be seen in [21].

Based on the analyses above, the BER formula is achieved under the effect of phase fluctuation caused by atmospheric turbulence, Costas loop and detector noise. Then, the effect of intensity variation of optical signal caused by atmospheric turbulence will be further considered here. As we know, the atmosphere turbulence will deteriorate the performance of laser beam propagation. For the intensity variation effect on optical signal caused by atmospheric turbulence, beam wander and intensity scintillation will be considered carefully in space uplink optical communication system.

The probability density function (PDF) of distance deviation caused by beam center follows Rayleigh distribution, which is expressed by [22]

$$P(r)=\frac{r}{\sigma_r^2}\exp\left(\frac{-r^2}{2\sigma_r^2}\right) \tag{26}$$

where r is size of the beam, σ_r^2 is variation of the beam wander, and parameters are given in [22].

Meanwhile, the probability density function of optical signal intensity caused by intensity scintillation can be calculated by [23]

$$P_I(r,L)=\frac{1}{\sqrt{2\pi\sigma_I^2(r,L)}}\frac{1}{I}\exp\left(-\left(\ln\frac{I}{\langle I(0,L)\rangle}+\frac{2r^2}{W^2}+\frac{\sigma_I^2(r,L)}{2}\right)^2/\left[2\sigma_I^2(r,L)\right]\right) \tag{27}$$

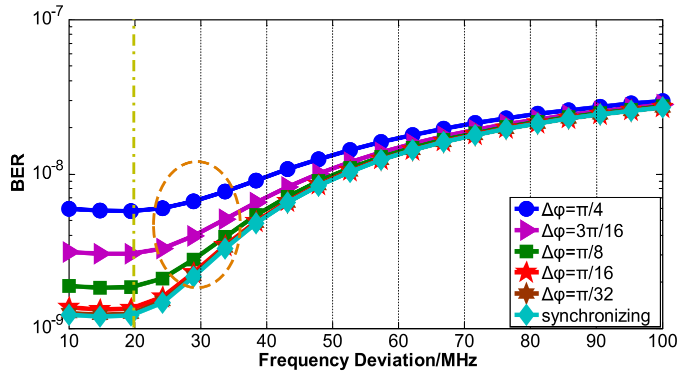

Fig. 2. BER versus frequency deviation for different phase deviations $\Delta\varphi$ of the Costas loop.

where $\langle I(0, L)\rangle = \alpha P_T D_r^2/2W^2$ is the mean intensify, P_T is the transmission power, D_r is the receiving diameter, α is the energy loss of the link, $W = \theta L/2$ is the radius of beam at the receiving plane, θ is divergence angle, r is the distance deviation between the beam center and receiving point, $L = (H - h_0)\sec(\zeta)$ is the length of the laser link, ζ is zenith angle, H and h_0 are heights of the receiver and the emitter, and $\sigma_I^2(r, L)$ is the variance [23].

Therefore, combining with intensity scintillation and beam wander, the PDF of receiving intensity under the influence of both scintillation and beam wander should be [22]

$$P_w = \int_0^{\infty} P(r)P_I(r, L)\, dr. \tag{28}$$

Consequently, taking consideration of intensity scintillation and beam wander caused by atmospheric turbulence effect, the BER with demodulation from the Costas loop is

$$\mathrm{BER} = \int_{-\infty}^{+\infty}\int_0^{+\infty} \frac{1}{2}\mathrm{erfc}\left(\frac{a\cos\kappa}{\sqrt{2}\sigma_n}\right) P_w(I) f(\kappa)\, dI\, d\kappa. \tag{29}$$

3. Simulation

Numeric simulations are based on the following parameters: frequency deviation is 50 MHz, quantum efficiency of APD $\eta = 0.75$, duration time $T_s = 1$ nm, $\lambda = 800$ nm, the detector amplification $G = 100$, additional noise factor $F = G^{1/2}$, spectral density of background light $I_B = 10^{-9}$ $\mathrm{Wm^{-2}nm^{-1}}$, zenith angle is 0, load resistance $R_L = 50\ \Omega$, energy loss of the link $\alpha = 1$, temperature $T = 300$ K, the height of terminal $h_0 = 100$ m, $H = 38\,000$ km, dark current $I_{dc} = 1$ nA, and the data rate is 100 Mbps.

As the phase modulation scheme is applied here, the phase fluctuation is an inevitable factor to analyze. Actually, the standard frequency deviation is an important parameter in phase fluctuation. Thus, it is necessary to analyze how this parameter influences the BER performance in an optical communication system. Fig. 2 shows the performance of BER versus the standard frequency deviation of atmospheric turbulence in different phase deviations caused by the Costas loop. From the figure, when the frequency deviation of atmospheric turbulence is lower than 20 M, all BER performance show relatively stable. It means the change of frequency deviation of atmosphere influences the BER rarely at lower level. It can also be shown that larger phase deviation of the Costas loop leads to the worse performance of transmission. It can be explained that the phase deviation of the Costas loop decrease the accuracy of produced carrier wave. As a result, it affects the BER performance during demodulation. Thus, the effect of phase deviation of the Costas loop plays a significant role when frequency deviation of atmosphere is low. On the

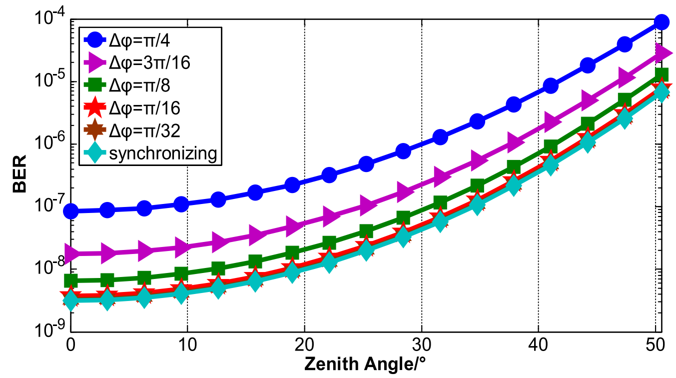

Fig. 3. BER versus zenith angle for different phase deviations $\Delta\varphi$ of the Costas loop.

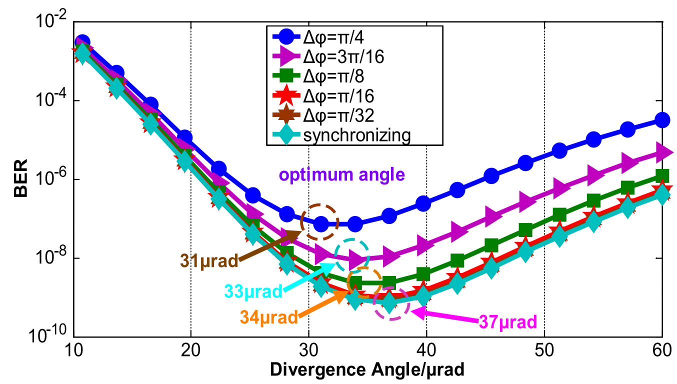

Fig. 4. BER versus divergence angle for different phase deviations $\Delta\varphi$ of the Costas loop.

other hand, with the growing of frequency deviation of atmosphere, the BER performance in different phase deviation of the Costas loop increases. When the frequency deviation of atmosphere is over 90 MHz, the BER performance in different phase deviations of the Costas loop seem approximately equal. It means that the BER performance, currently, is not sensitive for phase deviation of the Costas loop.

Furthermore, when the phase deviation of the Costas loop is lower than $\pi/16$, all the BER performance in three different phase deviations of the Costas loop $(0, \pi/32, \pi/16)$ are almost same. However, the BER performance of the other phase deviations of the Costas loop $(\pi/8, 3\pi/16, \pi/4)$ are various especially in the lower frequency deviation of atmosphere. This is very helpful for the design of practical system. For the great performance of propagation, the phase deviation caused by the Costas loop is better to be limited beneath $\pi/16$.

As is analyzed the performance of BER versus frequency deviation of atmosphere, zenith angle is also worthy to be explicated. With the zenith angle growing in Fig. 3, the BER performance of different phase deviations of the Costas loop increase. And the BER performances of different phase deviations of the Costas loop have nearly the same growth range. Specifically, when the zenith angle increases from 0° to 50°, the BER performance of all different phase deviations of the Costas loop have about 30 dB enhancement. Furthermore, BER performance is inevitably affected by phase deviation of the Costas loop at some specified conditions. Compared with synchronizing line, it produces about 15 dB, 7 dB, and 2 dB for BER performance with zenith angle of 20° when the phase deviations of the Costas loop are $\pi/4$, $3\pi/16$, and $\pi/8$. However, when the phase deviation of the Costas loop is limited by $\pi/16\,(0, \pi/32, \pi/16)$, the BER performance in this three different phase deviations of the Costas loop have been of almost same value. Consequently, BER is sensitive to zenith angle and the Costas loop need to be carefully designed for the optical communication system.

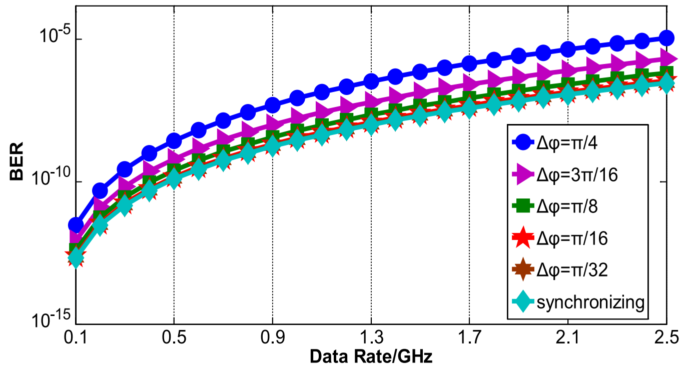

Fig. 5. BER versus data rate for different phase deviations $\Delta\varphi$ of the Costas loop.

Speaking of parameters of the receiving terminal, some other properties are necessary to research for analyzing the quality of propagation system. Fig. 4 shows the BER versus the divergence angle with different phase deviations of the Costas loop. It can be clearly seen from Fig. 4 that if the phase deviation $\Delta\varphi$ is limited by $\pi/16$, the BER performances are almost the same. However, when the phase deviation is larger than $\pi/16$ such as $\pi/4$, $3\pi/16$ $\pi/8$, the BER performance increase. Furthermore, there exists optimum divergence angle with the best BER performance. The optimum divergence angles are about 31 μrad, 33 μrad, and 35 μrad when the phase deviations of the Costas loop are $\pi/4$, $3\pi/16, \pi/8$ respectively. All the optimum divergence angles are about 37 μrad when the phase deviations of the Costas loop are 0, $\pi/32$, and $\pi/16$. These analyses are helpful for the optimization of receiving terminal with the best value of divergence angle.

Besides, data rate is another important parameter in practical system. Fig. 5 shows the BER versus data rate with different phase deviations of the Costas loop. Generally speaking, with data rate increasing, all the BER performance of different phase deviations caused by the Costas loop see the increase. When the phase deviation of the Costas loop is limited beneath $\pi/16$ shown as 0, $\pi/32$, and $\pi/16$, BER performance are almost same. However, it produces about 16 dB, 9 dB, and 2 dB for BER performance with data rate of 2.5 GHz when the phase deviations of the Costas loop are over $\pi/16$ like $\pi/4$, $3\pi/16$, and $\pi/8$. Thus, the phase deviation of the Costas loop is expected to be designed under $\pi/16$. These analyses mentioned above are very helpful for the design of high data rate communication in future.

4. Conclusion

The synchronization effect of the Costas loop on BER of BPSK space uplink optical communication system under atmospheric turbulence is analyzed. BER performance considering effect of the Costas loop under atmospheric turbulence in optical communication system is achieved. From simulation results, the standard frequency deviation caused by atmospheric turbulence influences the performance of BER. The BER performance decrease when frequency deviation of atmospheric turbulence grows up at a high extent. Besides, speaking of the parameters at receiving terminal, there has optimum divergence angle with the best BER performance in different phase deviations of the Costas loop. Furthermore, BER is sensitive for data rate and zenith angle, so they are important to pay much attention to the system design. When it comes to the Costas loop, the theoretical model and simulation results show that the effect of phase deviation caused by the Costas loop deteriorates the BER performance. As the result, the Costas loop should be designed meticulously for the better performance of BER. According to analyses from simulations, when the phase deviation of the Costas loop is designed under $\pi/16$, the BER performance are not sensitive for the phase deviation at this range for all system parameters and almost keep the same value. Thus, the phase deviation of the Costas loop is essential to be restricted under $\pi/16$ for the better BER performance. It can be implemented for the optimize phase deviation caused by the Costas loop. These results are helpful for the design of synchronization demodulation of the Costas loop system and can further enhance the communication quality in space optical communication system.

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