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A flexible receiver with fiber optical parametric amplifier in OCDMA-FSO communication system*

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A new receiver is proposed, which uses the fiber optical parametric amplifier (FOPA) in optical code division multiple access (OCDMA) over free space optic (FSO) communication system. The noise tolerance as the performance index in this receiver is derived. The receiver can not only improve the noise tolerance but also change the pump data conveniently for adapting to the length variation of the coding sequence under a complex and fast-changing weather condition. The influence of different factors on the noise tolerance is analyzed, and a significant improvement of about 18.77 dB for the noise tolerance can be achieved when the pump power and the length of coding sequence are 5 W and 256, respectively.

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In recent years, the free space optical (FSO) communication as the new wireless communication scheme has demonstrated great advantage on point to point communication[1]. However, it is particularly vulnerable to various weather condition[2] and atmospheric turbulence[3]. Many methods have been proposed to cope with the various weather condition and scintillation[4-10]. Optical code division multiple access (OCDMA) as a multiple access technique in optical communication has been used in FSO communication[6-10]. But the data decoding based on fiber Bragg grating (FBG) has a limitation that an FBG can only be applied to a coding sequence with a fixed length[10]. The fiber optical parametric amplifier (FOPA) has some advantages, such as large gain, broadband amplification and data transparency [11-16]. These characteristics can make it possible to receive the data in the OCDMA-FSO communication system.

In this paper, we propose a new receiver scheme which uses the FOPA in OCDMA-FSO communication system. This receiver is mainly composed of an FOPA and an accumulator. The receiver can not only decode the OCDMA data but also improve noise tolerance. Moreover, it is more flexible and effective to change the pump data for decoding the OCDMA data which is encoded by changing the length of coding sequence and is assembled in transmitter.

A receiver with FOPA for OCDMA-FSO communication system is shown in Fig.1. The encoded OCDMA data from all users is set as the input signal of FOPA. Fig.2 shows the data in an information window at the receiver. The encoded OCDMA data is composed of multiple users' information respectively encoded by several optical orthogonal codes (OOCs) which make up an orthogonal series, and it is denoted by $C_N(n, w, \lambda)$, where n and w are the length and the weight of this code, respectively[17]. When the Nth user's information is '1' (or '0'), its encoded data is '1' (or '0') $\times C_N(n, w, \lambda)$. λ is the correlation constraint and is set to 1. If the cross-correlation value between any two users' OOCs is '0' (or '1') at one time point, there are α '0' and $(N-1-\alpha)$ '1' to be assumed for cross-correlation value in the information window. The chip synchronization[18] and code asynchronization are assumed for OCDMA in this paper. The first user's encoded information has a delay which is expressed by t_{N-1} related to the Nth user's encoded information. If one user's information is received, this user's coding sequence should be set as the pump of FOPA which is signified by oblique striped area and repeated periodically. In Fig.1, both of the pump signal and the input signal are simultaneously loaded into a high nonlinear fiber (HNLF) to carry out the optical parametric amplification process. Then, the output signal of FOPA is received by the photo detector and accumulated periodically in electrical processing module. Here, the period is the same with the

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length of coding sequence. By setting the proper decision threshold, the decoded data is decided as '1' or '0'.

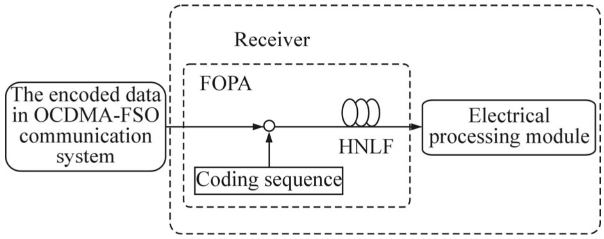

Fig.1 Architecture of the receiver with FOPA in OCDMA-FSO communication system

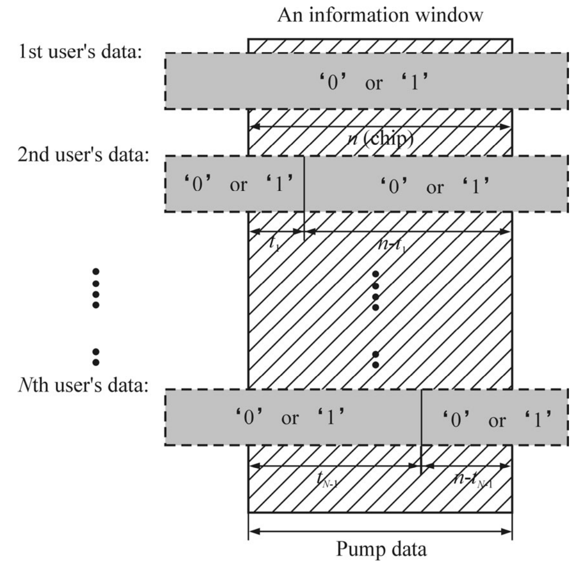

Fig.2 Asynchronous OCDMA data in receiver with FOPA for *N* users

As is well known, it is easier to determine if the noise tolerance is larger or not. We define the noise tolerance as the difference between upper limit and lower limit of decoding data for the first user. The upper limit is obtained at the accumulator output when only the first user's information is '1' in an information window in which the minimum of upper limit can be got and is used to decide '1'. Homologously, the lower limit is that only when the first user's information is '0' in the information window in which the maximum of lower limit can be got and is used to decide '0'.

For obtaining the noise tolerance, some definitions and calculations are necessary in FOPA. A pump and an input signal are coupled and transmitted into an HNLF with the length of L. P_P and P_S are the pump and signal power, respectively, γ is the fiber nonlinear parameter, and L_{eff} is the effective length of fiber. The signal at the fiber output is subjected to an amplification factor given as[19]

$$G_p = P_S(L)/P_S(0) = 1 + [\gamma P_P \sinh(gL_{eff})/g]^2 , \quad (1)$$

where $P_S(z)$ stands for the signal power at a distance z from the fiber input, and the parametric gain is

$$g = \sqrt{(\gamma P_P)^2 - (\kappa/2)^2} , \quad (2)$$

where κ is the nonlinear phase mismatch parameter.

If the phase matching is obtained, i.e., κ=0 and gL_{eff}>>1, the amplifier gain will increase exponentially with pump power.

We set the '0' and '1' bit power of the pump at the input of HNLF as $P_p^0(0)$ and $P_p^1(0)$, respectively. In this case, the signal can get two gains which are G_p^0 and G_p^1 depending on the bit transmitted by the pump. If the '0' and '1' bit power of the signal at the input is $P_s^0(0)$ and $P_s^1(0)$, respectively, the power of the signal at the fiber output can be obtain as[20]

$$P_{out}^{11} = G_p^1 P_s^1(0) , \quad (3)$$

$$P_{out}^{10} = G_p^1 P_s^0(0) , \quad (4)$$

$$P_{out}^{01} = G_p^0 P_s^1(0) , \quad (5)$$

$$P_{out}^{00} = G_p^0 P_s^0(0) . \quad (6)$$

For Eqs.(3)–(6) are effective, a requirement is important for ensuring gain which can occur, that is

$$P_p^0(0) - P_s^1(0) \geq 20 \text{ dB} , \quad (7)$$

which means that the difference between $P_p^0(0)$ and $P_s^1(0)$ must be 20 dB at least[21].

From the definitions above, we can conclude the upper limit and the lower limit when FOPA is operated in the linear regime. The upper limit is

$$wP_{out}^{11} + (n-w)P_{out}^{00} + \alpha[wP_{out}^{10} + (n-w)P_{out}^{00}] + (N-1-\alpha)[wP_{out}^{10} + (n-w)P_{out}^{00}] , \quad (8)$$

and the lower limit is

$$wP_{out}^{10} + (n-w)P_{out}^{00} + \alpha[P_{out}^{11} + (w-1)(P_{out}^{10} + P_{out}^{01}) + (n-2w+1)P_{out}^{00}] + (N-1-\alpha)[w(P_{out}^{10} + P_{out}^{01}) + (n-2w)P_{out}^{00}] . \quad (9)$$

The noise tolerance can be obtained as

$$NT = (w-\alpha)P_s^1(0)G_p^1(1 - \frac{1}{P_{out}^{01}/P_{out}^{00}}) \cdot (1 - \frac{wN-w-\alpha}{w-\alpha} \cdot \frac{1}{P_{out}^{10}/P_{out}^{00}}) . \quad (10)$$

By the derivation, it can be obtained according to Eqs.(3)–(6) that

$$P_{out}^{10}/P_{out}^{00} = G_p^1 P_s^0(0)/G_p^0 P_s^0(0) = G_p^1/G_p^0 , \quad (11)$$

$$P_{out}^{01}/P_{out}^{00} = G_p^0 P_s^1(0)/G_p^0 P_s^0(0) =$$

$$P_s^1(0)/P_s^0(0)=EX_{\text{input}}\ ,\qquad (12)$$

where EX_{input} is the input signal extinction ratio (EX). G_p^1/G_p^0 is related to pump EX, and it is monotonous increasing along with pump EX, but the increase tendency is more and more slow[11].

So based on Eqs.(11) and (12), Eq.(10) is updated to

$$NT=(w-\alpha)P_s^1(0)G_p^1(1-\frac{1}{EX_{\text{input}}})\cdot (1-\frac{wN-w-\alpha}{w-\alpha}\cdot\frac{1}{G_p^1/G_p^0})\ .\qquad (13)$$

The simulation setup is shown in Fig.3. A tunable laser at 1 554.08 nm is used as pump source. Through using three frequencies, the pump is modulated by phase modulator to suppress the stimulated Brillouin scattering. Then the modulated pump is loaded with a 100 Gbit/s return-to-zero (RZ) amplitude shift keying (ASK) signal which is repetitive coding sequence, and is amplified by a high-power erbium-doped fiber amplifier (EDFA) and filtered by an optical filter. Other tunable lasers are used as the signal sources at 1 572.82 nm for N users. They are loaded with a 100 Gbit/s RZ-ASK OCDMA signal. The pump and multiple signals are combined by a fused fiber coupler and subsequently sent to a 300 m-long segment of HNLF with zero dispersion wavelength of 1 554.0 nm. The nonlinear index and dispersion slope of HNLF are 17.1 m^2/W and 30 s/m^3 at 1 554 nm, respectively. The simulation is performed in commercially available software.

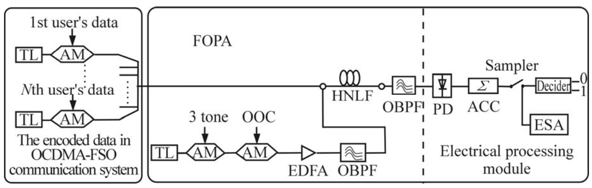

Fig.3 Schematic diagram of the simulation setup

After the optical parametric amplification process, a tunable optical filter is used to get the signal at the wavelength of an input signal. Then the signal at the filter output is detected by a fast-response photodetector (PD) and accumulated periodically by an accumulator (ACC). By selecting the sampling time and proper threshold in the decider, a data '1' or '0' can be obtained. In addition, the noise tolerance can be accurately obtained by the electronic signal analyzer (ESA).

When the input signal EX is varied, the noise tolerances for α=1 and 0 which respectively correspond to two users are recorded as shown in Fig.4. As Eq.(13) indicates, when the input signal power, the EX and the power of pump are constant, the noise tolerance is only related to $(1-1/EX_s)$ and changes slowly compared with the increasing input signal EX. The noise tolerances increase by 7.7 dB and 7.4 dB when a dynamic range of input signal EX is about 8 dB and α values are 0 and 1, respectively. When the weight of OOC is fixed, the noise tolerance is significantly deteriorated due to the increase of α. The difference between the two curves in Fig.4 becomes slightly larger along with the increase of signal EX.

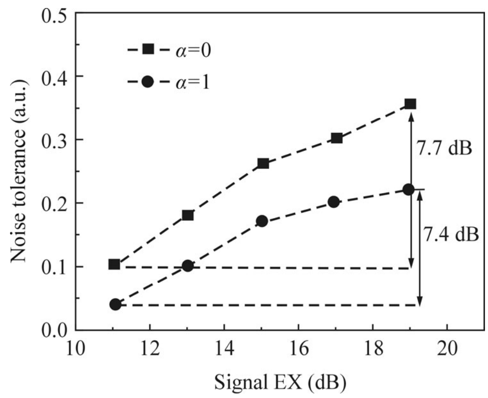

Fig.4 Measured noise tolerance of output signal versus input signal EX for two users

Fig.5 shows the variation of noise tolerance with input signal power when α=0 and 1, respectively. Because the input signal EX, the EX and the power of pump are constant, the curve is only related to $P_s^1(0)$ from Eq.(13). As the signal power increases from 0.1 mW to 1.0 mW, the noise tolerances are approximately increased by 11.55 dB/mW and 9.81 dB/mW linearly when α values are 0 and 1, respectively. So the influence of input signal power on noise tolerance is more direct.

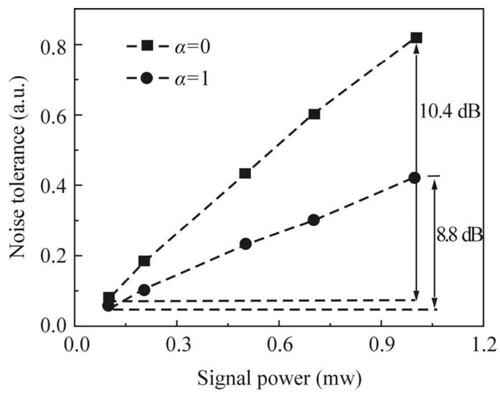

Fig.5 Measured noise tolerance of output signal versus input signal power for two users

When the EX and power of input signal and the pump power are constant, the noise tolerance is only related to $-1/(G_p^1/G_p^0)$ based on Eq.(13). As shown in Fig.6, when the pump EX is varied, the noise tolerance slowly changes compared with that of increasing pump EX for different α, and the rate of increase becomes more and more slow. This phenomenon is generated due to G_p^1/G_p^0 is monotonously increasing along with pump EX, and the increase tendency is more and more slow.

The noise tolerances are increased by 1.9 dB and 3 dB with a dynamic range of pump EX is about 8 dB when α values are 0 and 1, respectively. The difference between the two curves in Fig.6 has almost no change along with the increase of pump EX, and two curves almost keep rising at the same rate.

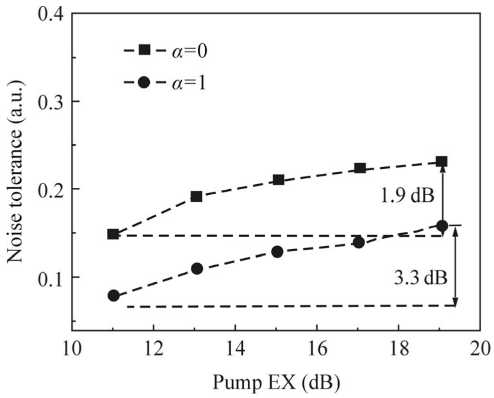

Fig.6 Measured noise tolerance of output signal versus pump EX for two users

As expected according to Eq.(13), Fig.7 shows that the pump power has large effect on noise tolerance. Because the pump gain increases exponentially with pump power due to the phase matching condition and the small signal power, the noise tolerance is also increased exponentially along with the pump power[19]. The noise tolerances are increased by 11.7 dB and 13.9 dB with a dynamic range of pump power is about 1.7 W when α values are 0 and 1, respectively. Pump power has more obvious influence on noise tolerance than other factors.

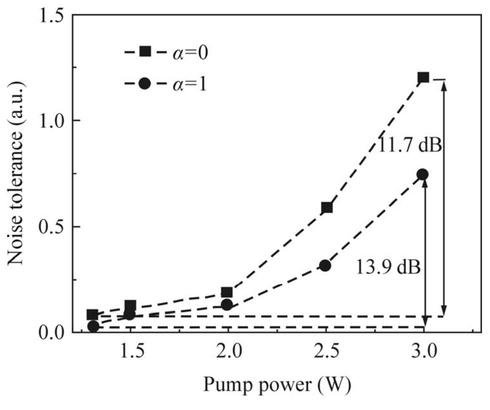

Fig.7 Measured noise tolerance of output signal versus pump power for two users

All of above analyses are based on fixed weight of OOC. From the first item of Eq.(13), we know that the weight of OOC can't be ignored because of the influence of multiplier effect. The item of $-1/(G_{\mathrm{p}}^{1}/G_{\mathrm{p}}^{0})$ in Eq.(13) is a fairly small value, so its coefficient item has little influence on noise tolerance. Fig.8 shows the variation of noise tolerance with the weight of OOC for different α of 0, 1 and 2, respectively. The noise tolerances are increased by 4.7 dB, 4.9 dB and 5.5 dB with a dynamic range of OOC weight from 3 to 6 when α values are 0, 1 and 2, respectively.

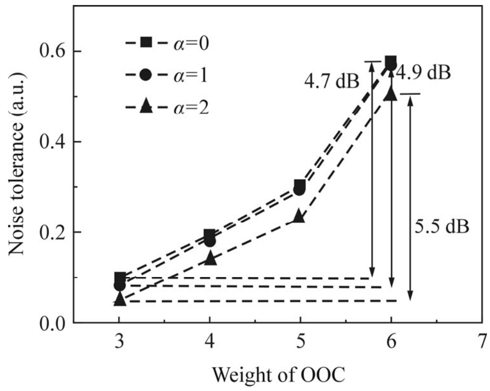

Fig.8 Measured noise tolerance of output signal versus the weight of OOC for three users

When an OCDMA-FSO communication system uses $C_N(32, 3, 1)$ as coding sequence for three users and with system bit rate of 100 Gbit/s, the coding sequence can be replaced by $C_N(n, w, 1)$ (n>32, w>3) according to system deterioration degree, although the user bit rate is reduced due to the fixed system bit rate. Fig.9 shows the variation of noise tolerance versus the length of OOC for different pump powers of 1.5 W, 3.5 W and 5 W, respectively, and the weight of OOC is simultaneously selected to be the maximum value for three users[22]. When the pump power is increased to 5 W, and OOC is replaced with $C_N(256, 9, 1)$ in OCDMA-FSO communication system, the noise tolerance is improved by 18.77 dB. By varying the length of user's coding sequence, it is simple to change the pump data in electrical domain and is not structurally limited as FBG[10]. So the receiver is effective to confront different weather conditions.

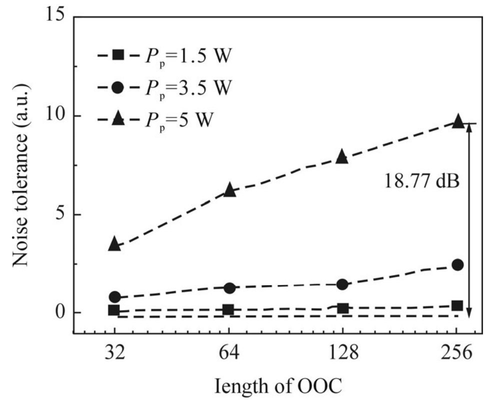

Fig.9 Measured noise tolerance of output signal versus the length of OOC for three users with different pump powers

In summary, a new receiver with FOPA for OCDMA-FSO communication system is demonstrated for the first time. The pump of FOPA is loaded with coding sequence and used as the decoding of the OCDMA data. It is convenient to change the pump data in electrical domain to adapt to different weather conditions. The noise tolerance is derived and set as the performance index in receiver, and the simulation results indicate that the EX and power of the input signal, the EX and power of pump, the weight and the length of OOC are all related to the noise tolerance. Input signal EX and pump EX are related to the noise tolerance by $-1/EX_s$ and $-1/(G_p^1/G_p^0)$, respectively, so they have relatively small effect on noise tolerance compared with other factors. When the pump power and length of OOC are increased to cope with the degraded weather condition, the noise tolerance is improved by about 18.77 dB. The proposed receiver in the paper not only can improve noise tolerance but also is convenient to change the pump data, so it is more flexible and adaptable for OCDMA-FSO communication system in complex and fast-changing weather conditions.

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