A novel technique for wireless optical communications with lenslet array processor

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A novel communication technique is proposed, which utilizes a set of mutually distinguishable optical patterns instead of convergent facula to transmit information. Then the capacity is increased by exploiting the optical spatial bandwidth resources. At last, we experimentally demonstrate the proposed communication technique based on four 8 × 8 spatial pattern signals by using lenslet array processor.

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The demand for wireless broadband communications has been growing steadily for last several years. Wireless optical communication holds the promise of delivering data rates that can meet the broadband requirements[1]. As a result, wireless optical is believed to be a viable long term option for many applications of wireless communications such as last-mile broadband access, inter-satellite links, and deep space connections. Nevertheless, as data are transmitted in serial forms at ever increasing bit rates, the ability to produce economical integrated support circuits may seriously curtail the practical exploitation of the bandwidth available in optical channels[2]. Thus the optical parallel characteristics are investigated to improve the communication performances[3,4]. However, it is studied mainly for parallel free-space optical interconnects in short interval.

In this paper another alternative novel technique is proposed, which exploits the optical spatial bandwidth resources to increase the communication capacity. In fiber communication and conventional wireless optical communication, the information is transferred by detecting the time-varying optical intensity. The signal of such communication system is simply limited to a single temporal dimension. Its communication capacity is defined by the random noise and bandwidth of modulator or detector. In fact, the channel of wireless optical communication includes both the temporal and the spatial dimensions. The volume between transmitter aperture and receiver aperture composes a low pass temporal-spatial channel. The information capacity is specified by the number of distinguishable optical patterns that can be transmitted through the wireless channel at unit interval. These optical patterns can be specified by the number of degrees of freedom N_f[5−7]

$$N_\mathrm{f} = \left(\frac{D_\mathrm{r} D_\mathrm{t}}{2\lambda z}\right)^2, \tag{1}$$

where D_r is the diameter of the receiver aperture, D_t is the diameter of the transmitter aperture, λ is the optical wavelength, and z is the communication distance. The information capacity of the communication system is

$$C = B_\mathrm{t} N_\mathrm{f} \log_2(1 + S/N)^{1/2} \quad \text{(bits/s)}, \tag{2}$$

where B_t is the temporal bandwidth, and S/N is the signal-to-noise ratio. Equations (1) and (2) show that the information capacity is increased by utilizing the spatial characteristics of optical system and the effect depends on the system geometry and the wavelength.

Selecting M mutually distinguishable spatial patterns instead of convergent facula for transmitting information can exploit optical spatial bandwidth resources. The optical pattern signal is generated by a spatial light modulator (SLM) with coherent light illumination or a two-dimensional (2D) vertical-cavity surface-emitting laser (VCSEL) array. The selected M distinguishable spatial patterns for communication can be expressed as

$$\mathrm{SP}^{(m)} = \begin{bmatrix} \mathrm{sp}_{11}^{(m)} & \mathrm{sp}_{12}^{(m)} & \cdots & \mathrm{sp}_{1N}^{(m)} \\ \mathrm{sp}_{21}^{(m)} & \mathrm{sp}_{22}^{(m)} & \cdots & \mathrm{sp}_{2N}^{(m)} \\ \vdots & \vdots & \vdots & \vdots \\ \mathrm{sp}_{N1}^{(m)} & \mathrm{sp}_{N2}^{(m)} & \cdots & \mathrm{sp}_{NN}^{(m)} \end{bmatrix},$$

$$m = 1, 2, \cdots, M, \tag{3}$$

where m indicates the serial number of the spatial pattern, matrix element $\mathrm{sp}_{ij}^{(m)}$corresponds to the irradiance of the pixel located at position (x_i, y_j) in spatial pattern. At the receiver end the spatial pattern is received by an imaging system. Based on maximum-likelihood decision rule[8], the received spatial pattern will be presented to a 2D correlator where cross-correlation is performed with M priori memorial spatial patterns. Then the received signal pattern can be decided by selecting the memorial spatial pattern corresponding to the largest correlation metric. The memorial spatial patterns are firstly transmitted to the receiver and stored in an electronic memory.

For the presence of noise, a received signal pattern cannot be defined exactly. The average probability of error decision for the received signal pattern can be expressed as

$$P_\mathrm{e} = (M-1) Q\left(\sqrt{\frac{E - r_{12}(0)}{2\sigma^2}}\right), \tag{4}$$

where $E = \sum_{i,j=1}^{N} (\mathrm{sp}_{ij}^{(m)})^2$ is looked upon as the power of

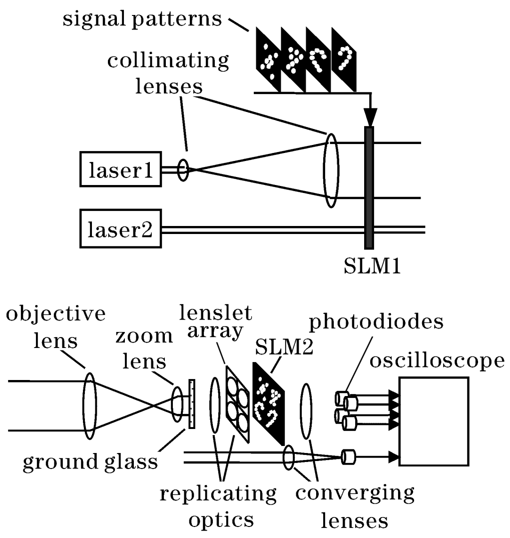

Fig. 1. Experimental setup.

an arbitrary signal pattern, $r_{12}(0) = \sum_{i,j=1}^{N} \mathrm{sp}_{ij}^{(1)} \mathrm{sp}_{ij}^{(2)}$ indicates the degree of cross-correlation between two arbitrary different signal patterns at a matched point, σ^2 is the variance of additive white Gaussian noise. From Eq. (4) we can see that the signal patterns should be designed for low cross correlation and sharp autocorrelations properties to decrease the error probability.

The experimental setup for demonstration is shown in Fig. 1. Laser1 is a 632.8-nm He-Ne laser, which is used for transmitting signal pattern. The diameter of laser beam expanded by collimating lenses is 55 mm. The expanded beam illuminates a twisted-nematic liquid-crystal (LC) SLM1. Then laser light is encoded spatially by the signal pattern and transmitted to the receiver. In this experiment, four signal patterns which are 8 × 8 pixels binary encoding are designed. The diameter of each pixel is about 1 mm and the interval of two neighbor pixels is about 2 mm. Each pattern has only eight transparency pixels. The cross-correlation of two arbitrary signal patterns at alignment position is zero. At any time, the transmitted signal pattern is randomly selected from the four signal patterns. Each pattern has the same probability to be transmitted. Due to liquid crystal SLM, the transmission speed is limited up to the video rate (30 fps). Laser2 is used for transmitting clock signal which is referenced to determine the time position of the received correlation peak. The wavelength of laser2 is also 632.8 nm. The distance of communication is 50 m.

At the receiver side, the signal optics is gathered and transformed to a reduced pattern image by an objective lens. The aperture diameter of the objective lens is 55 mm. Then the reduced image is magnified by a zoom lens and replicated on a ground glass. On the other side of the ground glass, an incoherent received signal pattern image RP is formed. The light from the received signal pattern displayed on the ground glass passes through a sphere and a four-element lenslet array that forms the replicating optics. The four lenses in the lenslet array produce four replicas of the received 8 × 8 pixels binary encoded image. The replicated images are produced on the SLM2 where four memorial patterns are modulated on it from a desktop computer. The memorial patterns are the received images of the four signal patterns. Figure 2 shows the received four signal patterns at the ground glass position after propagating 50 m. They are firstly transmitted to the receiver and memorized in the desktop computer for performing the matched-filtering operation. At the filter plane of SLM2, the received signal pattern image RP is multiplied separately with all the four memorial patterns

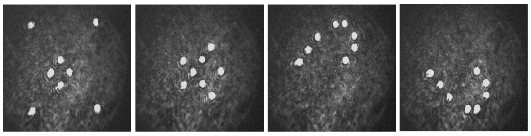
(a) (b) (c) (d)

Fig. 2. Received four signal patterns at the ground glass position after propagating 50 m.

$$\mathrm{rp}_{ij}\mathrm{sp}_{ij}^{(m)}, \quad m = 1, 2, 3, 4. \tag{5}$$

A converging lens maps the different spatial products onto a four-element photodiode array. Each photodiode corresponds to a particular signal pattern, with the photodiode implementing the crosscorrelation operation

$$\sum_{i,j=1}^{8} \mathrm{rp}_{ij}\mathrm{sp}_{ij}^{(m)}. \tag{6}$$

The outputs of each photodiode and clock signal from laser2 are input into an oscilloscope. Figure 3 shows the received signals displayed on the oscilloscope. The outputs of channels 1, 2, 3, and 4 correspond to the cross-correlation of the received signal pattern and the four memorial patterns in Fig. 2 which are modulated on the SLM2. The output of channel R2 is the clock pulse signal for reference. Above any clock pulse, there is only one correlation peak among the four output channels. The memorial pattern corresponding to this correlation peak is selected as the received signal pattern at the clock pulse time. Thus the received signal pattern at any clock pulse time can be decided by reading Fig. 3. In real applications, the decision of the received signal pattern can be completed by an electronic comparator.

At last, we discuss some problems of the proposed communication technique and attempt to present some suitable solutions. The first problem is that the signal power will be sharply attenuated by ground glass. It will shorten the communication distance and increase the

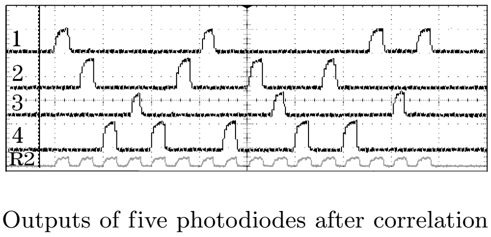

Fig. 3. Outputs of five photodiodes after correlation process with memorial patterns. Channel 1 correlated with Fig. 2(a); channel 2 correlated with Fig. 2(b); channel 3 correlated with Fig. 2(c); channel 4 correlated with Fig. 2(d); channel R2 is the clock signal from laser2.

decision error probability. To overcome this problem, a 2D spatial sampler is needed to replace the ground glass. The spatial sampler can be a photodiode array or CCD-detector array. After sampling, the received spatial pattern signal will be transformed to electronic signals fed to an amplifier which increases signal strength. Then the amplified electronic signals will be used to drive an electronic displayer to recover the received optical pattern signal fed to the lenslet array processor. Another problem is the alignment error of lenslet and mask pattern system. A longitudinal linear error and two angular errors will contribute both to image defocus and distortion. For this problem, a self-alignment method has been proposed[9]. The last problem is related to the matched-filtering operation. If the spatial pattern signals at transmitter are directly modulated on the SLM2 at the receiver as mask, the correlation process will not perform correctly, when the received signal pattern does not resemble in size or rotation to its corresponding transmitted spatial pattern. Hence, we propose the on-board reconstruction of matched filter. Before transmitting data information, each spatial pattern is firstly transmitted to the receiver to be used as matched filter. Then the correlations are performed with physically acquired data that take into account different link conditions such as optical channel turbulence in terms of scattering effects and relative transmitter and receiver orientations and locations, the system is designed for self-calibration, resulting in optimum decision with low error rate.

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