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All optical space-to-time mapping using modal dispersion of multimode fiber

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ABSTRACT

We experimentally demonstrate an all optical space-to-time mapping process using modal dispersion of large core high numerical aperture step-index multimode fiber in this paper. We use light beam with different input angle to excite various modes in a span of multimode fiber. The input optical pulses are stretched in time by modal dispersion and received by a large area, high speed photodiode. Through this process, the spatial information is directly mapped into device's temporal response. It has high speed, broad bandwidth and low system latency. Comparing with the widely used spectral imaging technology, this device is weak dependent of the input signal wavelength and optical carrier bandwidth.

1. Introduction

All optical space-to-time mapping can be used in ultra-fast optics [1], temporal imaging [2], optical pulse shaping [3] and processing applications [4]. Spectral imaging is a widely used technology that uses diffraction grating to disperse the wide band optical beam in different angle and encoded the spatial information into spectrum. Then the optical spectrum is detected by using other dispersion elements, such as diffraction grating [5] or optical fiber [6]. Thus, a wide band optical source is needed in such systems and the performance of these systems is often limited by the bandwidth of the light source. It may bring some inconveniences or high costs in some cases. Here we experimentally demonstrate an all optical space-to-time mapping process using modal dispersion in this paper.

As the capacity of optical systems based on single mode fiber (SMF) approach the nonlinear Shannon's limit [7], space-division multiplexing (SDM) including using multicore fiber and multimode fiber (MMF) is gaining prominence as the most promising technology for overcoming the capacity crunch [8]. Besides that, MMF has been used in many new applications, such as chromatic dispersion enhancement, making an optical integrator, a spectrometer or fiber-based endoscopes [9–11]. Since modal dispersion has very weak dependence on optical wavelength and bandwidth, modal dispersion based systems have the advantage of weak dependent of the input signal wavelength and optical carrier bandwidth [9]. The other benefit is its large dispersion comparing with chromatic dispersion, so the fiber needed to generate dispersion is very short. The space-spectra-time mapping using modal dispersion has been demonstrated in Ref [12]. In this paper, we establish the space-to-time mapping directly to make a cost-effective system. It needs no chromatic dispersive elements like diffraction gratings and wideband optical sources. It could provide compact highly dispersive responses and might have potential use in fiber-based endoscopy.

2. Basic theory

The spatio-temporal characteristic is one of the basic properties of optical devices. But it's often omitted, since it is hard to measure the spatio-temporal characteristics of an optical device because of the high speed of light. For example, when a narrow optical pulse is launched into space, it can be received by a photodiode placed as shown in Fig. 1.(a).

The distance from the light source to the photodiode is L. The arrival time of the optical pulse in different displacement will be related to the angle. The optical pulses will be stretched by the spatio-temporal delay, which can be calculated as $\tau = (L \tan\theta - \mathrm{L})/c$, c is the velocity of light. For example, if L=100 mm, θ=30°, the time delay is about 50 ps, which is so short that it's often omitted. The speeds of opto-electronic devices are getting higher and higher with the development of optical communication recently. Time delay of 50 ps can be measured clearly now. However, there is a fundamental tradeoff between the respond speed of the optical photodiode and its sensitive area. The respond speed of a photodiode is limited by its RC time constant or junction capacitance. The junction capacitance of a photodiode can be expressed

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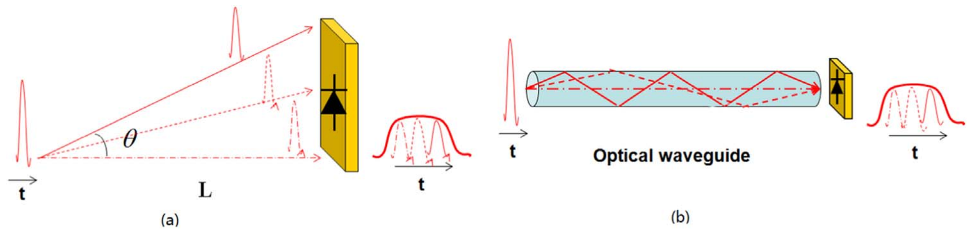

Fig. 1. Spatio-temporal delay measurement of optical devices (a) time delay in free space (b) time delay in free space in optical waveguide.

as [13]

$$C_j = \frac{\varepsilon_s A}{w} \quad (1)$$

in which ε_s is the capacitance ratio of the material. A is the area of the diffusion layer and w is the thickness of the depletion zone. Normally, the sensitive area of high speed photodiode is about several μm^2. The speed of the photodiode as shown in Fig. 1.(a) is always too slow to detect the corresponding spatio-temporal delay.

The optical beam can be confined in a very small space by optical waveguide. In a MMF, optical beam with different input angle can excite modes with different group delay because of the modal dispersion, so the optical pulses launched with large input angle will be stretched at the output end. In this way, the MMF can solve the contradiction of the photodiodes' respond speed and sensitive area, as shown in Fig. 1. (b).

The all optical space-to-time mapping process using modal dispersion includes two steps: Firstly, the different position in the object plane can be transferred into different input angle of the optical beam by a convergent lens. The modes in MMF can be excited by different input angle without considering mode coupling [14]. As we all know, the modal dispersion of MMF can be estimated by $\Delta t \approx n_1 \Delta / c = NA^2/2n_1 c$, n_1 is the effective refractive index of fiber, NA is the fiber's numerical aperture. To ensure the continuous of the output signal and generate large mode dispersion, we chose large core, high numerical aperture step-index MMF which has lots of modes. Secondly, the optical signals in different modes transmit through the MMF by different group velocity, which can be expressed as

$$t_{mn} = \frac{d\beta_{mn}}{d\omega} \quad (2)$$

In which, β_{mn} is the transmission constant of a certain mode.

To simulate the modal dispersion of MMF, we choose a span of MMF whose core diameter is 200 μm and numerical aperture is 0.37. Using MMF with large NA is helpful to improve the resolution of the system. The number of modes in the MMF is more than 2800. The transmission constant and the group delay of different modes are calculated and shown in Fig. 2(a) and (b), respectively. Traditionally, the modal dispersion of step index MMF is not linear. However, as shown in Fig. 2(b), in large core diameter, high numerical aperture step index MMF, the modal dispersion is very close to linear. It can be used in spatio-temporal mapping.

Numerical simulation is done to explore the spatio-temporal mapping characteristics of MMF. The output energy distribution as a function of input excitation angle in the presence of mode coupling can be obtained by numerically solving [16]. If we focus an off-axis Gaussian beam into the MMF, with the maximum angle of the beam to the center of the MMF, the Gaussian distribution of the input beam may counteract the zero order Bessel function of the output energy distribution and a uniform energy distribution among the modes can be got.

The output energy distribution of an off-axis Gaussian beam can be calculated as:

$$\varepsilon(\theta, z) = \sum_{n=1}^{\infty} a_n I_n J_0\left(b_n \frac{\theta}{\theta_c}\right) \exp\left(-\frac{D b_n^2 z}{\theta_c}\right) \quad (3)$$

The coefficients a_n are given by:

$$a_n = \frac{2J_0\left(b_n \frac{\theta}{\theta_c}\right)}{\theta_c^2 J_1^2(b_n)} \quad (4)$$

where b_n are the zeros of the Bessel function J_0. In the case of oblique plane-wave excitation, θ is the center angle of the angular distribution of excited modes in the fiber, θ_c is the critical angle inside the fiber, D is the mode coupling constant, and z is the length of the multimode fiber. I_n is the optical intensity of the input beam with input angle that can exciting the nth mode.

The simulation results of Eq. (3) are shown in Fig. 3. Fig. 3. (a) shows the angular distribution of the output beam with a plane-wave excitation in 50 m MMF. Its output energy distribution is an infinite sum of zero order Bessel function. If we focus an off-axis Gaussian beam into the MMF, a uniform energy distribution among the modes can be got, as shown in Fig. 3. (b). The coupling constant of (a) and (b) are D=1*10^{-5}[16]. The curves with different color are excited by different input angle. The output angle is almost the same with the input angle, but the output angles are broadened to overlap with the adjacent beam because of mode coupling. In a strong mode coupling

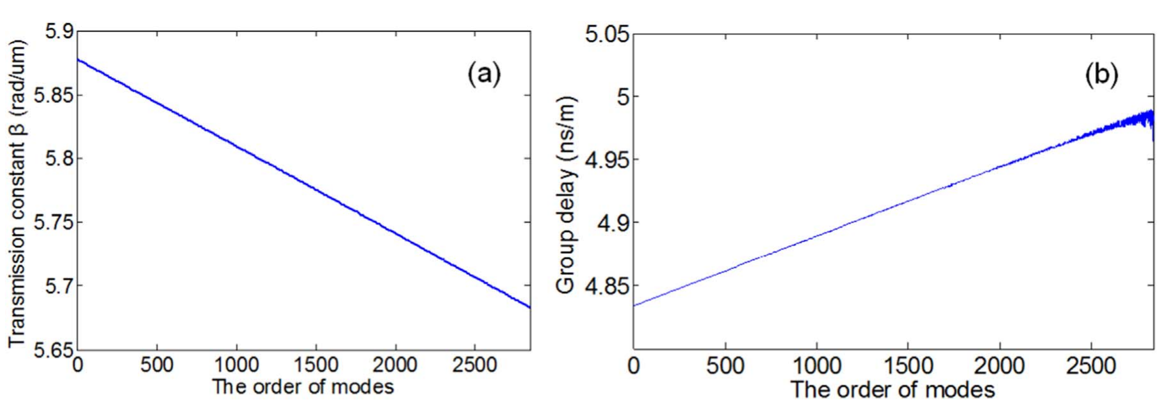

Fig. 2. The simulation result of the group delay of MMF. (a) the transmission constant against the order of modes. (b) The group delays of the fiber against the order of modes.