Spectral Space-Time Coding for Optical Communications Through a Multimode Fiber

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Abstract: We propose a method for coding the mode structure of a multimode optical fiber by spectral coding mixed with space-time modulation. With this system we can improve the data carrying capacity of a multimode fiber for optical communications and optical interconnects, and encode and decode the information in the spectral and time domain using the aperture area of the fiber at the same time. The results of our preliminary experiments and simulations toward this goal are presented.

Introduction

During the last decades there have been numerous attempts to utilize the mode structure of multimode fibers for communications. One of the earliest appeared in mid-70s where the multimode nature of fibers was used for image transmission [1]. Later, holographic modal demultiplexing has even been used to set up an experimental ring/star LAN employing fiber mode properties [2]. A recent study has extended these to take into account the intrinsic scattering between the modes [3]. Although this latter approach needed multiple laser-detector pairs and complex signal processing, nevertheless, it pointed out to the potential of a partially diffuse medium, such as Plastic Optical Fiber (POF) [4] to improve the communication capacity utilizing space-time coding [5].

The advantages of POF technology [6] come from reasons including relaxed connector tolerances, economical fabrication methods, and a large range of polymer optical circuit devices [7] for all-optical signal processing. The latest studies have shown that the multimode PF GI-POF can be a high bandwidth transmission medium [8] with the possibility of high-speed data transmission [9] at 11 Gbits/s in the normal communications wavelength range through 100m. These, together with the fact that a dispersion delay of about 200ps can be observed depending from the launch conditions [10], is also a clue to test the feasibility of our idea with POF. The main emphasis of the present paper is to utilize both the spatial and spectral mode properties of such multimode fibers to our benefit in order to take a different view over the actual coding ideas

Spectral space-time coding

The basic idea present in this text consists of using a broadband light source together with a spectral coding device to project a spectrally labeled spatial light pattern onto the entrance aperture of a multimode fiber. This provides a distribution coded in (λi,xi,yi), a spectral and spatial way, as shown in Fig. 1.

The two main optical components, for transmission and reception respectively, used to implement the spectral coding, possible within the system of Fig.1, can be based on the light controlled nonlinear-optical resonator structures. More specifically, the selection of a bunch of spectral components for different spatial positions over the aperture of the fiber is achieved by an inhomogeneous array of optical resonators with light controlled resonance peaks selected according to the desired spectral content. Some more details and simulated results on these components will be given below.

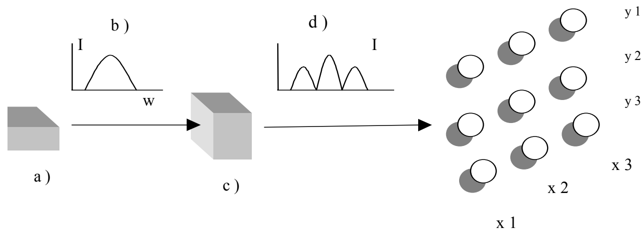

Fig. 1: *A spectrally sliced broadband light source used to project a 2D spatial pattern with spectral coding. a) Broadband source; b) original spectrum; c) spectral coding; d) sampled spectrum. The 2D pattern on POF entrance with spectral (wavelength) coding.*

The experiments on mode patterns

Finding out the behavior of the information under conditions of spatial coding is basic in order to include it in our signal processing technique. Toward this goal we implemented a set up that, basically, consist on a broadband source (multimode GaAlAs) with its light focused onto a PMMA fiber (1mm and 60microns core, 1m length) and, finally, we detect the output pattern. This set up allows us to check the degree of deviation of output light from the uniform distribution as a result of changing the launch conditions.

Fig. 2 shows some patterns resulted from this experiment that give a good example of the successful transmission of spatial information through a fiber. Furthermore, this effect is also observable under changing conditions of the launching beam. This opens new possibilities of getting different distributions playing with the variables we use to code our light spatially. At the present time, we are studying such results in order to get some more conclusions on the feasibility of our coding method.

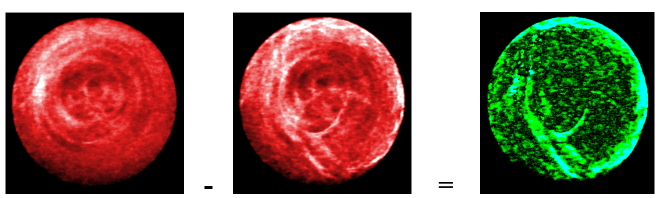

Fig. 2. P*hotographs of two POF output intensity patterns after being processed to reduce noise. The left one was generated by a beam launched near to the center of the core, whereas the second was generated by light injected near to the edge of the core. The image on the right shows the difference between the levels of intensity on each spatial point in these two patterns on its left.*

Possible methods for coding and launching the input

At the present time, the straightest way to implement an encoder at the input of the multimode fiber for our purpose is to introduce the light from the broadband source into a geometrical 1D-to-2D taper array. We then implement the nonlinear tunable resonator structure described above on each one of the fibers of the taper. Such a resonator can use a 3rd order non-linear optical effect for coding the information spectrally. With the help of the fiber-taper, this resonator can be implemented in 1D as a nonlinear Fabry-Perot like the structure, illustrated in Figure 3. In this figure, we see that a light pattern incident on this resonator is changing the transmission pattern by modifying the effective resonances embedded therein. As a result, we would basically have a non-linear tunable grating array selecting our spectral lines.

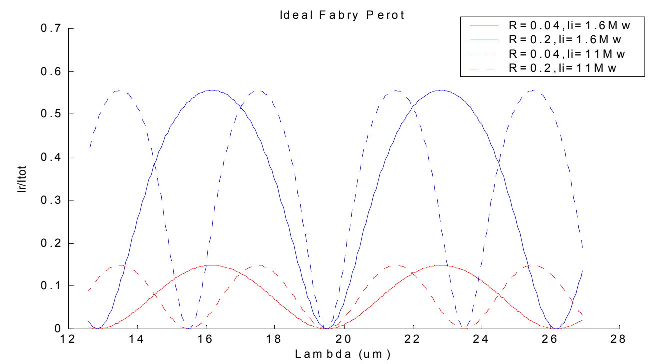

Fig. 3*: Nonlinear Fabry Perot resonator as an example of the possibilities of coding the information spectrally.*

Guided-Mode and Speckle-Mode-Beating simulations

In this section we propose some signal processing techniques, to decouple the information from a mode multiplexed fiber. In a first approach we observe that it is possible to influence the intensity and the spectrum of the pattern at the output of the fiber by the spectral coding at the input, Fig. 4. On the other hand, we can use the properties of the available technologies in order to increase the degrees of freedom of our coding system. A photodiode detects the power at each spatial point at the output of the fiber. It receives photons with the frequencies we have propagated form the beginning of the fiber, but their subtraction and addition too, Fig. 4 right. This means that we can code not only the frequencies we propagate but the low frequency mode-beating spectrum of the photodetector. In conclusion, with these results, it is possible to establish a method in order to code the information, not only for working with the launch conditions, but also using the dependence of the different frequencies.

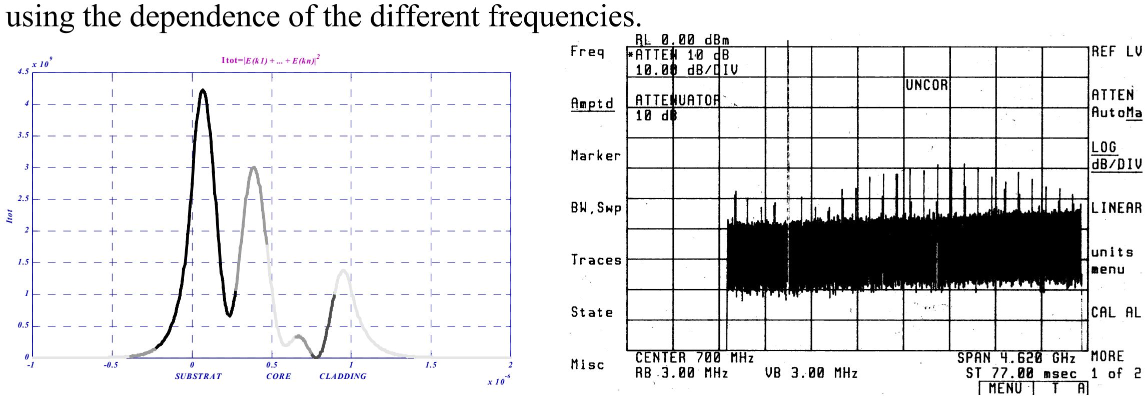

Fig. 4*: On the left is the spatial distribution of light output as result of propagating modes with 4 different spectral components through POF. Each one excites the first ten TE modes. Each gray level represents the area where each frequency has major influence over the intensity. On the right, measurements of the low frequency mode-beating spectrum of a photodetector facilitating the labeling of mode structures. This experiment was implemented with an Ar laser in order to eliminate any power problems at the detection.*

Capacity

The capacity of spectral space-time coded multi-mode fiber channel can be estimated by adapting the corresponding theory for wireless communication channels with antenna arrays. We recall that, in this case, the received signal vector, **y**, is obtained from the transmitted signal vector, **x**, using the relationship on the left below, where **H** is the normalized communication channel matrix, in our case, of the POF. The capacity, C in [(bits/s)/Hz], of the multi-channel is then given by the expression on the right

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix} \times \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \qquad C = \log_2 \left\{ \det \left[I + \frac{S\,HH^*}{N\,n} \right] \right\}$$

where, **I** is the identity matrix, S/N is the signal to noise ratio in (dB), and n is the number of transmitters/receivers, which are assumed to have the same value. Note that the capacity is determined by the rank of the channel matrix, **H**. The exact gain, however, is a function of the matrix components, which in turn are dependent on the correlation between the different channels of the medium.

In our study, the input vector has additional degrees of freedom in the spectral domain, in terms of different wavelengths, on top of the space-time domain. Based on the discussion given above, this obviously helps the capacity by increasing the rank of the matrix. Furthermore, it adds opportunities to tailor communication signals by choosing spectral components which minimize correlation between adjacent channels. In practice, we expect that these two coding components will provide us with a new design parameter to optimize POF communications against the inter-channel correlation and intra-channel dispersion.

Discussion and conclusions

With the help of preliminary experiments and numerical simulations we have demonstrated some of the operational principles of our method for spectral modulation of space time-coded communication signals for multi-mode fibers. It is possible to control, propagate and recover the spatial correlation between the channels of a multimode fiber by utilizing spectral code which could be detected by a simple photodetector as beat frequencies. We have also indicated a few possibilities for the implementation of spectral (de)coding based on non-linear Fabry-Perot structures which could be used either in reflection of transmission mode.

In spite of these encouraging results, we indicate remaining problems associated with sensitivity of the modes of the fiber to the external perturbations. We believe however, these will be at much lower time scales than the communication speeds leading to the possibility of solving such problems by adaptive (de)coding methods which could even be implemented in the optical domain.

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