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Letters to the Editor

Transmission of picture (analog) information by a multimode optical fiber

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The paper deals with a transmission of a picture by a single multimode fiber. The imaging effect was obtained by using the phase conjugation method. Experimental results, especially the imaging resolution, are presented.

1. Introduction

The investigations carried out in recent years allow us to state that the principal factors which cancel a picture information transmitted by a multimode fiber are the following [1]–[4].

i) Different phase velocity of fiber modes (modal dispersion)

This problem results from the nature of light propagation in the fiber and is described thoroughly in [1], [5]. It can be explained by using the formulas

$$S_0(x,y) = \sum_j A_j \Psi_j(x,y), \tag{1}$$

$$S(x,y) = \sum_j A_j \Psi_j(x,y) \exp(-i\beta_j l) \tag{2}$$

where: $S_0(x,y)$ – input picture field,
$S(x,y)$ – output field obtained at the end of a fiber,
l – fiber length,
Ψ_j – eigenfunction associated with the mode j,
β_j – propagation constant, characteristic of the mode j,
A_j – expansion coefficient.

Because of model dispersion, the factors A_j, φ_i are multiplied by different phasors $\exp(-i\beta_j, l)$, thus the signals S_0 and S are different, even in an ideal fiber. The radiation modes (not available at the output face of the fiber) in Eqs. (1) and (2), can be omitted, because the image distortion due to radiation is negligible if compared with blurring, caused by dispersion effect in a perfect fiber [3].

ii) Microdefects appearing in feasible manufactured fibres, located stochastically along and across the fiber

When the technology of optical fibers is not perfect enough, there appear in fibers some "macrodefects", such as nonuniformity of both the refraction index profile and geometrical profile nonuniformity (symmetrical or nonsymmetrical changes of radius of a core and a clad, and ovalization of fibers' circular cross-section). Additional defects (micro-cracks) arise due to the reeling of fibers. The above mentioned imperfections lead to intermode scattering, modal attenuation and additional radiation. Finally, the output field at the end of a fiber differs from the field described by Eq. (2). Because of the diverse and accidental character of defects, the problem of light propagation along the manufactured fiber is very complicated. Finally, there is no useful theoretical approach to the problem of connection of the input picture signal S_0 with the output signal S in a nonideal fiber.

Two methods of using the optical fiber cable for the transmission of information signals can be distinguished.

i) Transmission of light pulses by a fiber

The pulses are frequency- or amplitude-modulated. The action of the fiber is similar to that of an electrical cable in information radio links. In this case the single mode fibers with low attenuation and low modal dispersion are preferable, if the spread-pulse effect is to be avoided. The method reveals, however, serious disadvantages, because even simple picture information has to be decomposed into separate pixels. The signals dealing with proper pixels are transmitted successively by the fiber, and next put together into the output picture. The necessity of the picture decomposition and its composition seriously increases the transmission time and limits throughput of information.

ii) Direct transmission of a complete picture information by the fiber

This method is very promising; it avoids the inconvenience inherent in the former method, a complete information being transmitted in the same moment, the throughput of information increases automatically. For this purpose, the multimode optical fiber can be used. In this case, the bound modes of the fiber are elementary information carriers. Because of modal dispersion and the mentioned defects in the fiber, the output field is different from the input picture. Hence, the reconstruction of the input information is a main problem in this method. The problem can be regarded as that of the optical inverse.

The paper deals with the latter method and is devoted to the restoration of the input picture information, transmitted by a multimode fiber. The experimental results, illustrating the effectiveness of the image transmission by a multimode optical canal are given.

2. General

The optical inverse problem, i.e., the recovering of the input picture signal can be explained in our case as follows. Let the function G describe the field of the optical source. In our experiments G is an information field at the input face of the fiber. The light field at the end of the fiber is given by the function F. The optical inverse problem consists in finding the operator Ω, which transforms the field F into the field G $(\Omega F = G)$.

In the experiment performed by the authors, the operator was realized practically by the phase conjugation method [1], [6]. The latter assures an explicit realization of reproducing the operator Ω. The operator achieved experimentally transforms the output field of the fiber (S) into the field S_0^*, complex conjugate of the input field S_0. The irradiance distributions of input and recovered signals are identical, because

$$I = |S_0|^2 = |S_0^*|^2. \quad (3)$$

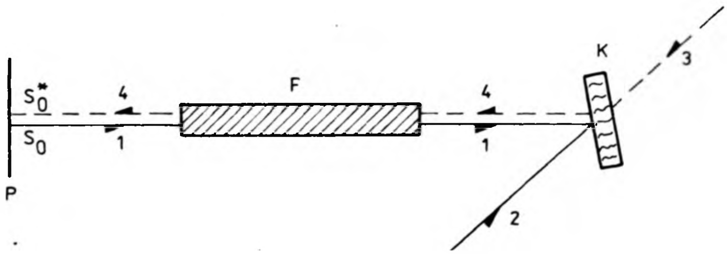

Fig. 1. Experimental arrangement: 1 – input beam carrying picture information, 2 – reference beam, 3 – reading beam, 4 – phase conjugate beam retraversing the fiber (F – fiber, K – element generating a phase conjugate signal, P – observation plane of the input signal S_0 and the recovered conjugated signal S_0^*)

The scheme of experimental arrangement is presented in Fig. 1. The information light beam, spatially modulated by the input picture is marked by a continuous line, while the phase conjugate beam retraversing the fiber is marked by a broken line. K is an element with an optical memory, producing the phase conjugate signal. The setup presented in Fig. 1 is an impulse system. The mutually coherent beams, 1 (passing through the fiber) and 2, generate a volume interference pattern inside the element K. It stores the distorted signal S when the input signal S_0 is switched off. Then, after illuminating by the reading beam 3, the element K emits the signal S^*, which is phase conjugate of cancelled signal S. The field S^* retraverses the fiber and, due to its conjugated form, the mutual delays of mode phases disappear when the field propagates through the fiber. Finally, the restored signal S_0^* appears in the observation plane P.

3. Experiment

The setup was similar to that presented by DUNNING and LIND [3]. The lithium niobate crystal, dopped by iron [7], was in our experiments used as the element K. Mutually coherent signal beam 1 and reference beam 2 (Fig. 1), emitted by argon laser ($\lambda = 488$ nm), recorded the volume hologram in the crystal. The beam 3, counterpropagating to the beam 2 (Fig. 1), reconstructed the hologram and, consequently, the conjugated signal retraversing the fiber was generated. A microscopic objective formed microimage of the picture signal S_0 at the input of the fiber. We have investigated two cases, i.e., when either a microimage in the form of Fourier image (the centre of the input face of the fiber matched the focus of an objective) or a spatial image of the signal S_0 was projected onto the input face of the fiber. A better quality of the output conjugated image S_0^* was obtained in the latter case. In the experiment we used the multimode step-intex fiber 1 m long with N.A. of 0.2 and diameter of 250 μm.

The results of picture imaging by the fiber, obtained in different cases, are shown in Figs. 2 and 3. We could estimate the resolution of imaging, using the Simens test as the input signal S_0 (Fig. 3**a**). The details of the spatial microimage from the input of the fiber up to 100 lines/mm, were reconstructed in the output conjugated image. From experimental results it appeared that resolution was mainly limited by speckle nature of the recovered image. The clear speckles in the output image (Figs. 2, 3) were formed due to the interference of the bound modes of the fiber. The experimental measurements have confirmed our hypothesis that the resolution is determined by the diameter of the speckle.

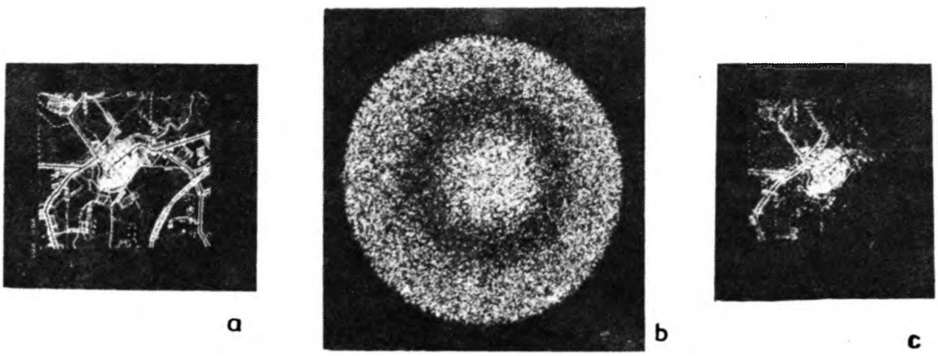

Fig. 2. Input picture signal S_0 (a fragment of a map) – **a**, distorted signal which passed through the fiber (image information is completely cancelled – **b**, and output signal reconstructed by the phase conjugation method **c**

Fig. 3. Examples of three different output picture signals transmitted by the fiber: **a** — Simens test, **b**, **c** — binary tests

The output conjugated signals shown in Figs. 2 and 3 were achieved after the light had passed and retraversed the same piece of the fiber. The recovered signal at the output of the system is not completely identical with the input picture. The differences between the signals depend on the quality of the fiber. The measurement of the loss information at the output can be used for investigations concerning the defects in manufactured fibers and for the estimation of fibers quality.

The principal purpose of our study is the construction of an analog fiber link for a distant transmission. Such a link requires two identical pieces of fiber of the same parameters [1], [2], [6]. It is a complicated problem, because inhomogeneities and defects in manufactured fibers make the matching of two fibers of identical parameters difficult. The proper investigations, dealing with this problem are being carried out in our laboratory.

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Перенос изображений через многомодное оптическое волокно

В настоящей работе представлены результаты пропускания оптических сигналов (изображений) через одно многомодное волокно с использованием зеркала обратной связи. Представлены экспериментальные результаты, а особое внимание уделено разрешающей способности метода.