Investigation of mode coupling in optical fiber with controlled volume disorder

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ABSTRACT

This paper presents results of experimental and theoretical studies of light transmission through optical fibers with disorder generated in its germanium-doped core via UV radiation transmitted through a diffuser. The experimental results on transmission of the radiation of 543 nm wavelength demonstrate the presence of the disorder in the core of the optical fiber – beyond a certain characteristic length, the transmitted power is observed to be distributed over all modes of the fiber. A theoretical model based on coupled mode theory is developed. An analytical expression for the mixing length is obtained and agrees well with the experiment. For long sections of disordered fiber, the experimentally measured distribution of the near-field intensity at the output surface of the fiber is well described by the Rayleigh negative exponential function. This suggests a statistically uniform distribution of the transmitted power over all modes, that agrees with the prediction of the theoretical model. The reported technique provides an easy way to fabricate different configurations of controlled disorder in optical fibers suitable for such applications as random fiber lasers.
Keyword: multiple scattering; disordered fiber optics; coupled mode theory.

INTRODUCTION

In recent years, there has been a considerable interest in optical disordered media. This is largely due to the important benefits observed when disorder is induced into a mundane system. A random laser[1], where laser action is ensured by a coherent feedback in disordered structures, such as powders or porous crystals, is a striking example. In the paper[2] the advantages of disordered systems in wireless communications of high information capacity have been shown. It has also been reported[3] that the disorder induced in nonlinear crystals can greatly improve the efficiency of operation of nonlinear optical devices. It appears that disordered media open numerous possibilities for applications in sensors, nanophotonics and, more generally, in varios system of light transmission.

In this report we present experiments on fabrication of random variations of the refractive index throughout the core of a Ge-doped optical fiber, whose parameters can be controlled in our experimental setup. The characteristics of the created disorder are evaluated from an analysis of the intensity distribution of the near-fields at the output of the fiber and by the analysis of the speckle size dependence of the total intensity of the transmitted light. The experimental results are compared, and agreement is found, with the predictions of the coupled mode theory, which is adapted to the particular type of volume disorder considered in this work.

FABRICATION OF THE DISORDER

The experimental setup utilized for the fabrication of disorder in optical fibers is schematically depicted in Fig.1. In our experiments we employed the step-index optical fiber (PS1250/1500 of Fibercore) sensitized by Ge. The main parameters of the fiber are: the core diameter is 7.66 microns, the cladding diameter is 125 microns, NA = 0.13 with the refractive indexes of the core and the cladding 1.463 and 1.457, respectively. The cutoff wavelength of the fiber with these parameters was about 1200 nm. The volume disorder was introduced in the Ge-doped fiber core by exposing it to UV light from an intracavity frequency doubled Argon-ion laser (244nm) which passed through a cylindrical lens and a diffuser, creating, in this way, a speckle pattern in the plane parallel to the fiber axis. The light beam generated by the UV laser was initially expanded by a cylindrical lens with a focal length 12 cm in order to form the necessary spot width on the diffuser plane. The beam transmitted through the diffuser was used for

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exposing the photo-sensitive fiber. Speckle, as the strongly fluctuating, grainy intensity pattern resulting from the interference of randomly scattered coherent waves, resulted in fluctuations of the illuminating UV intensity in the fiber core. The average speckle spot size is defined as[4] $r = \frac{\lambda D}{\pi \omega}$ where D is the distance between the diffuser and the fiber axis, ω is the diamater of the illuminated region in the diffuser plane, and λ is the wavelength of the recording light. Variations of the D in the range 2-8 mm and of ω in the range of 8-10 mm allowed us to obtain the average speckle size between 200 and 600 nm.

The length of each segment with the fabricated disordered L_s was 1-2 cm. The experimental geometry allowed us to record the segments with greater lengths (5 cm). In order to achieve disorder with similar statistical parameters in each segment, the same exposure time was used for all segments, namely, about 10 minutes at a mean power of the UV laser about 100 mW. We observed experimentally that after this exposure the intensity distribution of the output probe light at the fiber output did not change. Every next segment with a random distributed of the refractive index was recorded directly after the preceding one. The total lengths of the fabricated disordered part were 2, 4, 6, 8, 10 and 15 cm. It is noteworthy to mention that fabrication of the longer samples was not necessary because, after passing 8 cm of the disordered fiber, the transmission saturates and practically stops changing with an increase of the disordered part of the fiber.

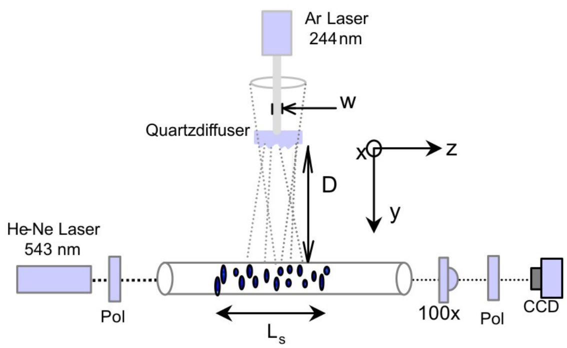

Fig1. The experimental setup.

After forming the bulk disordered segment we launched the probe beam of the He-Ne laser operated at $\lambda = 543$ nm into the fiber, and detected the image of the output intensity distribution by a charge-coupled device (CCD camera, ST-402ME SBIG). The selected wavelength 543 nm of the probe beam ensured a low mode-number propagation regime and corresponded to the sensitivity range of the CCD camera quite well. The light emerging from the fiber passed through the microscope objective x100 which imaged the output fiber plane on the CCD camera. In front of the CCD camera there was a polarizer utilized for characterization of the transmitted light.

EXPERIMANTAL RESULTS

The resulting V parameter of the utilized fibers was 5.8171 at the probe wavelength, and the expected number of the guided linearly polarized LP_{lm} modes is 20. By varying the angle of the of incidence of probe beam, different combinations of modes were excited and the corresponding near-field transmitted intensity was recorded. It appears that these measurements can be made quite reliably. Indeed, (i) the light polarization was preserved in the fiber without disorder; (ii) the ambient temperature fluctuations did not change significantly the parameters of the fiber samples during measurements. At the input of the optical fiber, the polarized light goes through a half wave-plate and a linear polarizer. The output light was detected separately for both polarizations: a) after passing through a polarizer of the same orientation as at the input (pp - polarization) or b) perpendicularly polarized (ps - polarization). We analyzed the the output light of each polarization independently. The polarization extinction ratio of the laser source and the fiber output was measured in the linear transmission regime.

Examples of the intensity distribution of the light emerging from the fiber, obtained for different realizations and for different angles of the incident beam with the disordered segment of the fiber of 1 cm (a) and 2 cm (b) long, are presented in Fig.2. The left column corresponds to pp-polarization measurements, the right columns represents ps – polarization measurements. Different realizations were obtained by slightly bending of the disordered part of the fiber.

In Fig. 3 the ensemble averaged intensities of the output light measured experimentally as functions of the length of the disordered parts of the fiber (L_s) are presented. The averaging was performed over 10 realizations. One can see that increasing the angle of incidence, which increases the weight coefficients for the higher order modes, the chacteristic length of the mode coupling goes down. The solid line corresponds the curve $T = C - \exp(-L/\ell_{mixing})$, where C=-0.02 and ℓ_{mixing}, the characteristic (mixing) length, equals 5.5 cm.

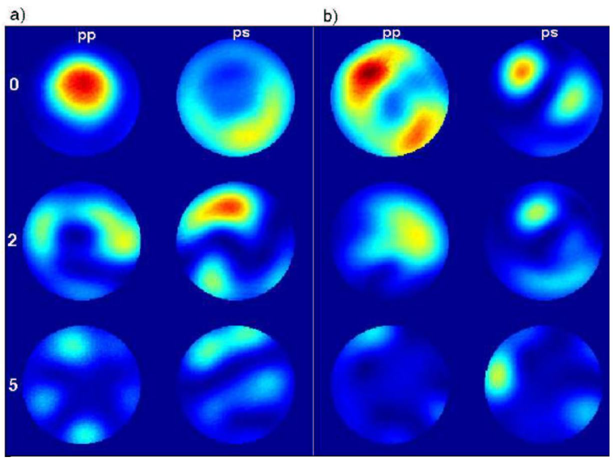

Fig.2. Examples of the intensity distribution observed in some realizations with the disordered part of the fiber 1 cm (a) and 2 cm (b) in length; the left column in each figure presents pp – polarized distribution, and the right column presents the ps – polarized one. The angles of incidence are 0^o, 2^o and 5^0 from the upper to the bottom images.

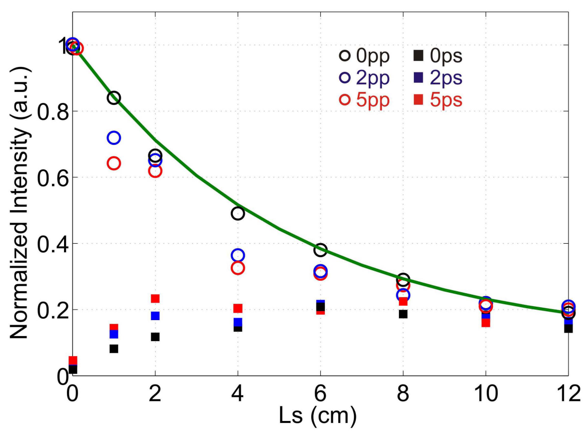

Fig. 3. Experimentally observed total transmission as a function of the length of the disordered part of the fiber. The black symbols correspond to an angle of incidence of 0^o, the blue symbols to 2^o, and the red ones to 5^o .

COUPLED MODE THEORY IN FIBER WITH BULK RANDOM PERTUBATION OF REFRACTIVE INDEX

The data presented in Figs. 2, 3 suggests that the random fluctuations of refractive index imprinted in the core of a photo-sensitive fiber result in mixing among different propagating modes. To describe this process and to obtain the characteristic (mixing) length of the disordered segment of fiber, we employ the coupled-power method developed by Marcuse [5]. However, because the disorder induced by the UV speckle pattern does not allow a factorization of the refractive index modulations into the functions of the transverse and longitudinal coordinates δn(x, y, z) = δn(x, y)×f(z), the original derivation is not applicable. We demonstrate that the coupled mode theory can still be developed due to the factorization of the disorder's second order correlator

$$\left\langle \delta\varepsilon(\vec{r})\delta\varepsilon(\vec{r}\,')\right\rangle = \left\langle \delta\varepsilon^2 \right\rangle \exp\left[-\left(\frac{x-x'}{S_x}\right)^2\right] \times \left[1+\left(\frac{y-y'}{S_y}\right)^2\right]^{-1} \times \exp\left[-\left(\frac{z-z'}{S_z}\right)^2\right]$$

where $\delta\varepsilon(\vec{r})$ is the fluctuation of the dielectric function due to presence of disorder and $S_{x,y,z}$ correspond to the speckle dimensions. The derived equation

$$\frac{dP_\mu}{dz} = \sum_\nu \left[h_{\mu\nu}P_\nu - h_{\mu\nu}P_\mu\right]$$

describes the evolution of the disorder-averaged power in each mode P_μ. The obtained expression for the coupling coefficients (not shown here due to space considerations) allows one to compute a characteristic length after which modes become perfectly mixed. Its expression can be simplified to obtain the following analytical result

$$\ell_{mixing}^{-1} \sim \frac{\Delta n}{2n_{core}} \frac{\pi\omega^2 S_x S_y S_z}{c^2 a^2},$$

where a is the core radius. Substituting the experimental parameters of the system we find $\ell_{mixing} \approx 5$cm. The agreement with the experimental data shown in Fig. 3 is good, given the fact that the exact value of Δn is not directly accessible, we estimated it to be of the order of 10^{-4}.

One known prediction of a coupled mode theory is that the power is *equally* distributed over all modes of the fiber [5]. The fact that the intensity transmitted through the long sections of the disordered fiber reaches a saturation (within experimental precision) beyond L=15cm agrees well with the theoretical predictions. It also suggests that the coupling to the radiative modes and other loss mechanism do not play a significant role in transmission. The conclusion that a perfect mixing (in statistical sense) occurs in our experimental system can also be tested through measurements of the statistical distribution of the polarization-resolved near-field intensity. Indeed, a random sum of different modes of the fiber is expected [6] to result in the Rayleigh negative exponential distribution. This predict based on the above theory is fully borne out experimentally.

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