Study of spatial–temporal characteristics of optical fiber based on ultrashort-pulse interferometry

R. Rokitski, P.-C. Sun, and Y. Fainman

Department of Electrical and Computer Engineering, University of California, San Diego, 9500 Gilman Drive, La Jolla, California 92093-0407

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We demonstrate a method for reconstruction of the modal intensity distribution of light at the output of an optical fiber. Spatial modes of the optical fiber are separated in time as a result of differences in group velocity and are detected experimentally by observation of the interference of the modal field distribution with the time-gating reference field. The detected interference patterns of the modal fields are analyzed, providing the spatial impulse response of the fiber. We also use interferometric correlation to determine the spatiotemporal characteristics of the fiber modes, such as pulse width, linear chirp, and group velocity, for each mode. © 2001 Optical Society of America

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For successful high-speed signal transmission through a multimode optical fiber both the spatial and the temporal impulse responses of the fiber must be known. Propagation of the optical field in a multimode fiber can be difficult to predict in detail. Each excited mode is usually perturbed by various factors (fiber bends, junctions, thermal effects), depending on the mode order. These perturbations are usually distributed randomly along the transmission line and do not vary rapidly with time. The effect of the perturbations is almost unpredictable theoretically but can be estimated experimentally and used for channel equalization. Therefore, experimental measurement of impulse response is crucial for high-speed data transmission through a multimode fiber. It was shown[1] that for short distances (~1 km) the intermodal coupling is small and that therefore the total impulse response at these distances can be approximated as a sum of impulse responses that correspond to different modes. Several techniques were developed to excite and detect fiber modes selectively,[1–4] and these techniques can be used to measure the impulse response of each mode individually. These methods employ either different masks for selective launching and detection or side launching and detection of the light that is leaking from the etched fiber. To our knowledge there was only one experiment[5] in which the phase and group velocities of different modes were measured. This experiment required special preparation of the fiber: The cladding was etched at the output, allowing different modes to leak from the core at different angles. Light that corresponded to different fiber modes was observed in the far field as a set of rings, with each ring corresponding to a specific fiber propagation mode. Time variation of this ring pattern, achieved with a picosecond streak camera, allowed the phase and group velocities of individual modes to be estimated. Here we introduce and experimentally evaluate a new technique for spatiotemporal characterization of multimode light propagation in the optical fiber. Our method is based on time-resolved interferometric measurements with femtosecond optical pulses, providing femtosecond temporal resolution. It allows the spatial distribution of the electric field at the fiber output to be measured as a function of time and the linear chirp of the output pulse to be estimated.

When a short pulse $p(z, t)$, propagating as a plane wave in the z direction, is launched into a multimode fiber, it excites several spatial modes. We assume that nonlinear effects are negligible and that propagation of the pulse is affected only by group-velocity dispersion (intermodal) and a combination of material and waveguide dispersion (intramodal). The pulse appears at the output as $S(\mathbf{r}, t) = H(x, y, t; z) * p(z, t)$, where $H(x, y, t; z)$ is the impulse response of the fiber link, including the input coupling part, $*$ denotes convolution in time, $\mathbf{r}$ is a radius vector with components x, y, and z, and we assume that the input and the output cross sections of the fiber lie in the xy plane. The fiber impulse response $H(x, y, t; z)$ depends linearly on fiber length z, assuming that the fiber is translationally invariant in the z direction. If the intermodal coupling is weak, each mode propagates along the fiber independently and appears at the output as a short pulse. The total impulse response is then approximated by $H(x, y, t; z) = \sum_\nu h_\nu(x, y, t; z)$, yielding the total output from the fiber, $S(\mathbf{r}, t) = \sum_\nu h_\nu(x, y, t; z) * p(z, t)$, where h_ν is the impulse response of mode ν. The initial temporal distribution of the optical field is the same for all the excited modes; however, the output characteristics of the pulses are different, because different modes have distinct group velocities and intramodal dispersion. Therefore a single short pulse coupled into a multimode fiber appears at the output as a series of pulses that correspond to different spatial modes of the fiber, as illustrated in Fig. 1. To characterize completely the propagation of a short pulse through a multimode fiber we need to obtain both the temporal and the spatial distributions of the optical field for each mode.

Our technique is based on the cross correlation of an optical field that has unknown spatial and

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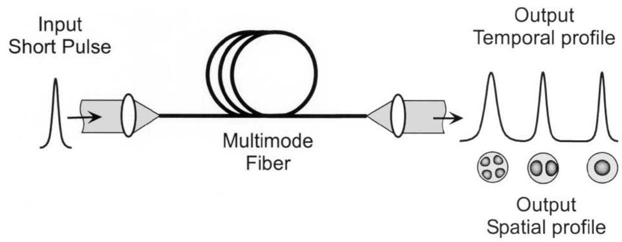

Fig. 1. Propagation of an optical pulse in a multimode fiber. A single input pulse excites a set of spatial propagation modes of the fiber, which appear at the output at different times.

temporal profiles with a known reference field. We gate the output electric field from the fiber, $S(\mathbf{r}, t) = S_0(\mathbf{r}, t)\exp[-j(\omega_0 t - \mathbf{k}_1 \cdot \mathbf{r})]$, using a transform-limited reference pulse with a relative delay τ: $R(\mathbf{r}, t + \tau) = R_0(\mathbf{r}, t + \tau)\exp\{-j[\omega_0(t + \tau) - \mathbf{k}_2 \cdot \mathbf{r}]\}$. Our technique employs a Mach–Zehnder interferometer that detects the intensity distribution of the interference pattern between $S(\mathbf{r}, t)$ and $R(\mathbf{r}, t)$ that is generated for the various time delays τ. In our notation $R_0(\mathbf{r}, t)$ is a real amplitude of the reference field and $S_0(\mathbf{r}, t) = |S_0(\mathbf{r}, t)|\exp[j\phi(\mathbf{r}, t)]$ is the complex amplitude of the signal field emerging from the fiber; $\mathbf{k}_1$ and $\mathbf{k}_2$ are the wave vectors of the signal and the reference fields, respectively ($k_1 = k_2 = \omega_0/c$). The output intensity yields $|S_0(\mathbf{r}, t)|^2 + |R_0(\mathbf{r}, t + \tau)|^2 + \langle 2|S_0(\mathbf{r}, t)|R_0(\mathbf{r}, t + \tau)\cos[\mathbf{k}_2 \cdot \mathbf{r} - \mathbf{k}_1 \cdot \mathbf{r} - \omega_0\tau - \phi(\mathbf{r}, t)]\rangle$, where $\langle\,\rangle$ denotes time averaging over an interval much larger than the optical period $2\pi/\omega_0$. The total intensity is a sum of intensities of the signal and the reference waves, the interference signal with spatial carrier frequency $\Delta\mathbf{k} = \mathbf{k}_2 - \mathbf{k}_1$, and the phase shift $\omega_0\tau + \phi(\mathbf{r}, t)$. By performing a spatial Fourier transform and spatial filtering the intensities, we can separate $\mathcal{F}\{|S_0|^2\}$ and $\mathcal{F}\{|R_0|^2\}$, centered at zero frequency (dc term), from the cross term $\mathcal{F}\{\langle 2S_0R_0\rangle\}$, which is shifted by the spatial carrier frequency $\Delta\mathbf{k}$. Because the signal pulse is chirped, the interference patterns that correspond to the leading and the trailing edges of the reference pulse have slightly different spatial carrier frequencies and a relative phase shift. We assume that the femtosecond-pulse bandwidth is much smaller than the carrier frequency ω_0, and consequently these effects are negligibly small compared with the spatial carrier frequency $\Delta\mathbf{k}$ and the width of the spatial spectrum $\mathcal{F}\{S_0\}$. For successful spatial filtering it is desirable to make $\Delta\mathbf{k}$ as large as possible; however, in practice $\Delta\mathbf{k}$ is limited by the spatial resolution of the detector (CCD camera). After filtering out the dc term of the spatial spectrum, we obtain $\mathcal{F}\{S_0\}*\mathcal{F}\{R_0\}$. We obtain the desired modal intensity distribution by taking the inverse spatial Fourier transform $\mathcal{F}^{-1}\{\mathcal{F}\{S_0\}*\mathcal{F}\{R_0\}\}$ and normalizing the result by R_0. By varying relative time delay τ and analyzing output signal $S_0(\mathbf{r}, t)$, one can measure the temporal impulse response of a multimode fiber. Our method can also be used to measure the temporal characteristics of separate spatial modes. This can be achieved by choice of a fiber that is long enough that different modes propagating with different group velocities appear at the output of the fiber separated in time. The separation needs to be larger than the reference pulse width to permit characterization of each mode. The interferometric correlation data can be used for quantitative estimation of the ultrashort pulse dispersion,[6] allowing us to obtain from the measured data the linear chromatic dispersion of the fiber for each mode. As a result, spatiotemporal information about pulse propagation in the multimode fiber is obtained; the characteristics so quantified include the pulse width, the linear chirp, and the group velocity of each spatial mode.

The experimental setup for mode observation at the output of the optical fiber is shown in Fig. 2. The short optical pulse from a mode-locked Ti:sapphire laser source (MIRA 900; $\lambda \sim 920$ nm, pulse FWHM $\sim$200 ps) is divided by a beam splitter between the two arms of a Mach–Zehnder interferometer. One of the interferometer's arms contains 3 m of step-index Corning SMF-28 optical fiber with an 8.3-μm core diameter. At a 920-nm wavelength this fiber supports two spatial modes. A $4f$ imaging system with a magnification factor $F/f = 275\times$ is used to image the signal wave from the output of the fiber onto the CCD camera. The signal wave also is recombined by a beam splitter with the reference wave from the other arm of the interferometer to form an interference pattern upon the surface of the CCD. The period and the direction of the observed fringe pattern are defined by the difference between wave vectors $\mathbf{k}_1$ and $\mathbf{k}_2$ of the signal and the reference waves, respectively. The polarization of the signal wave is adjusted by a polarizer to yield the maximum contrast of the interference pattern. The reference wave is spatially filtered, expanded, and collimated to approximate a plane wave. To observe interference, we set the optical path difference between the two arms to be equal to the distance between two adjacent pulses ($\sim$4 m) from the pulse train that is generated from the mode-locked laser with a pulse repetition rate of 77 MHz. We performed time-domain scanning in 0.33-ps steps by using a delay line in one of the arms of the interferometer. The observed interference patterns that correspond to the LP_{01} and LP_{11} modes are shown in Fig. 3(a). The patterns are free of optical speckle because they are separated in time and have contrast ratios of $\sim$0.5 and $\sim$0.14 for modes LP_{01} and LP_{11}, respectively. We detect an interference pattern by using a high-resolution CCD camera interfaced with a computer and perform all the subsequent image processing numerically,

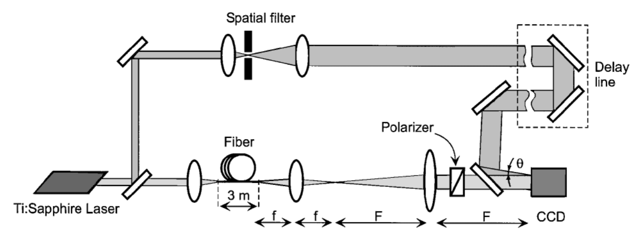

Fig. 2. Experimental setup for interferometric cross-correlation measurements.

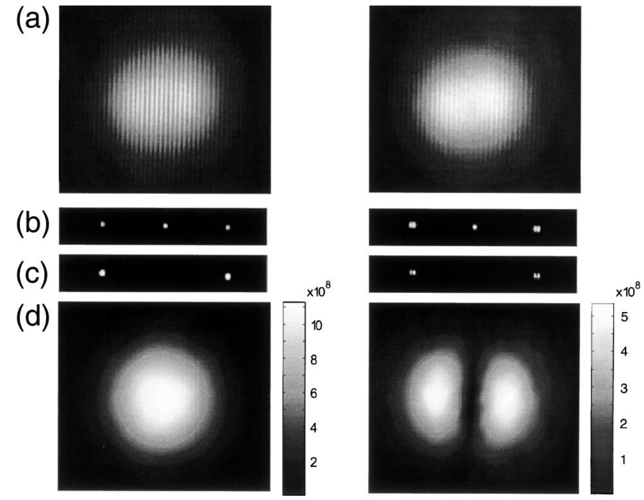

Fig. 3. (a) Interference patterns, observed for two relative time delays, separated by $\Delta\tau \sim 6$ ps. Two-dimensional spatial Fourier spectrum (b) before and (c) after filtering, showing dc and ac terms in each case in the center and on the sides, respectively. (d) Reconstructed modal intensity distributions corresponding to left, LP_{01} and right, LP_{11} modes.

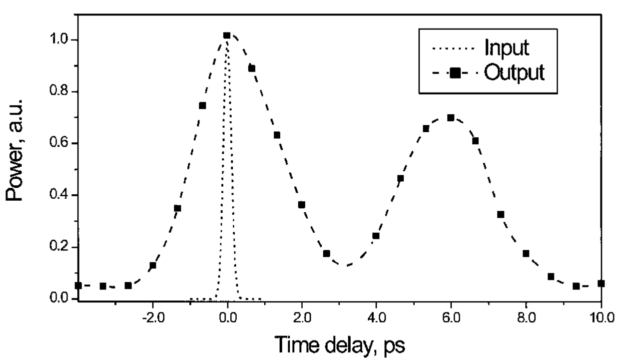

Fig. 4. Optical power at the fiber output for several time delays.

following the procedure described above. The spatial Fourier transform of the detected interference pattern [Fig. 3(a)] is shown in Fig. 3(b) (the origin of the spatial frequency corresponds to the center of the images). To show both the dc and the ac terms of the spectrum we applied nonlinear gray-level mapping to compensate for the large amplitude difference between the terms. The dc term as well as noise is reduced by use of a filter function with a $0.5 + 0.5\,\mathrm{erf}(\mathbf{k} - \Delta\mathbf{k} - w)\mathrm{erf}(-\mathbf{k} + \Delta\mathbf{k} - w)$ profile, where $\Delta\mathbf{k}$ is the previously defined spatial frequency of the interference pattern and w is the filter width. After applying the filter function [Fig. 3(c)], we perform an inverse Fourier transform of the one-sided spectrum to return to the space domain and extract the magnitude of the transform and remove the linear phase term $\exp(j\Delta\mathbf{k} \cdot \mathbf{r})$. Because the spatial mode of the reference beam is magnified to approximate a plane wave, calibration is simplified. In this case, reference wave $R_0(\mathbf{r}, t)$ is a constant, and an inverse Fourier transform gives the desired spatial intensity distribution for the fiber modes, as shown in Fig. 3(d) for the two time delays. In our experimental setup the mode coupling is weak but the length of the fiber is chosen to be sufficiently long to separate the modes in time; therefore these intensity distributions represent modes LP_{01} and LP_{11} of the optical fiber. Repeating the procedure for several time delays of the reference pulse, we obtain the temporal–spatial distribution of intensity at the output of the fiber. Integrating the intensity distribution across the fiber aperture for each time delay gives the temporal distribution of power, as shown in Fig. 4. From Fig. 4 we estimate the output pulse widths to be ~2.2 and ~2.4 ps for modes LP_{01} and LP_{11}, respectively. Assuming only linear material dispersion, we can estimate the group-velocity dispersion[6] as $\beta_2(\lambda = 0.92\ \mu\mathrm{m}) = \Delta\tau/(L\Delta\omega)$, where $\Delta\tau$ is the pulse spread, $\Delta\omega$ is the pulse spectral width, and L is the propagation length. This expression for β_2 gives the group-velocity dispersion, $\beta_2 \sim 75\ \mathrm{ps}^2/\mathrm{km}$, assuming a sech^2 input-pulse shape. Two peaks, which correspond to modes LP_{01} and LP_{11}, are separated by ~5.6 ps, yielding an $\sim 8 \times 10^4$ m/s group-velocity difference, assuming that the group index is $n_g(\lambda = 0.92\ \mu\mathrm{m}) = 1.46$.

We have demonstrated the application of an ultrashort-pulse laser and a Mach–Zehnder interferometer arrangement to analyze spatial and temporal characteristics of the modes in optical fibers. This technique allows the spatial intensity distribution and the optical impulse response of the fiber to be measured. The spatial resolution of the setup is diffraction limited, whereas the temporal resolution is defined by the pulse width of the mode-locked laser. The sensitivity of the method is determined by the total number of and power distribution between the excited modes. For a large number of excited modes the contrast ratio degrades, limiting the sensitivity of the technique. In this case nonlinear detection by one of the well-known methods[7] can be employed.

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