INVESTIGATION OF ULTRASHORT CLADDING PULSES GENERATED IN SINGLE MODE OPTICAL FIBERS

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1. Introduction

Optical fibers are used to transmit light when flexible and low loss transportation is required from one place to another. With the simple principle of total internal reflection, light can propagate through the fiber’s core. The violation of total internal reflection and/or the illumination of the cladding results in that the light propagates not only in the core but also in the cladding. Some applications require coupling light into the cladding. There are sensors based on optical fibers, where the coating of the fiber is removed thus its modal composition depends on the surrounding ambient, for example temperature [1-3]. Another application of cladding modes is to produce Bessel beams. A light „ring” exiting the cladding can be collimated with a lens, which creates a beam profile of a Bessel function [4, 5]. However, in most cases coupling into the cladding ought to be avoided in ultrashort laser pulse technology.

A way to investigate the modal composition of fibers is intermodal interference [6]. Here the higher order modes are interfering with the base core mode and they create spectral interference, which allows us to investigate the modes in the time domain by performing an Inverse Fast Fourier Transform (IFFT) on the measured spectra [7]. By making cross-scans of the beam, the fiber’s modal composition can be characterized spatially, which is called the S^2 method [8, 9].

Single mode fibers support the propagation of only one mode in the core. To our best knowledge the propagation of ultrashort laser pulses in the cladding of single mode fibers has not been investigated yet. In this work the interference of the core and the cladding pulses is studied by the S^2 method after the collimation of the output beam from a single mode fiber.

2. Theory

A single ultrashort laser pulse has a smooth spectrum and after performing an IFFT, only one signal is present near $t = 0$ in the time domain as depicted in Figure 1. However, if there are two pulses with $\boldsymbol{\tau}$ time delay between them, the spectrum becomes modulated. Evaluating the modulated spectrum with IFFT, two signals are obtained in the time domain, one is at $t = 0$, while the other one is at $t = \boldsymbol{\tau}$. If there are multiple pulses, the spectrum becomes even more modulated corresponding to every pulse delayed by $\boldsymbol{\tau_i}$ time, which results in multiple peaks after IFFT.

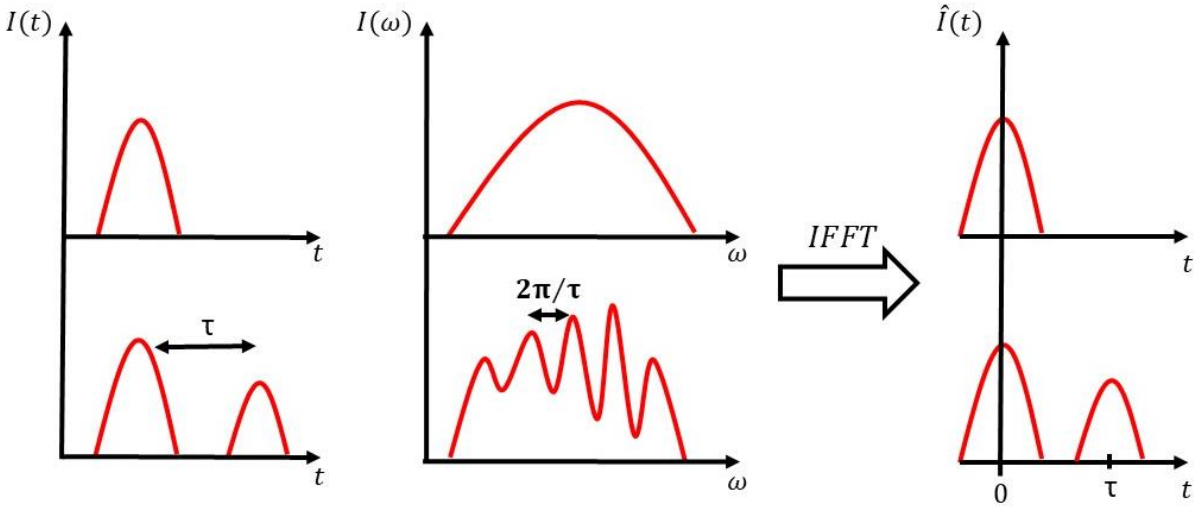

Fig. 1. Spectrum and its IFFT signal for a single laser pulse (top) and for two pulses with a time delay τ (bottom).

In our case the two pulses interfering with each other are the core pulse and the cladding pulse. To satisfy the total internal reflection, the refractive index of the material of the cladding is smaller than the core's refractive index. As a result, any pulse entering the cladding propagates faster than the core pulse and a time delay between the core and cladding pulses exiting the fiber is produced, which results in spectral interference. Figure 2 shows how the cladding pulse (red curves) interferes with the core pulse (blue curves). Due to cylindrical symmetry the intensity of the interference is highest along the optical axis. There can be interference at other spatial points as well, but with lower intensity.

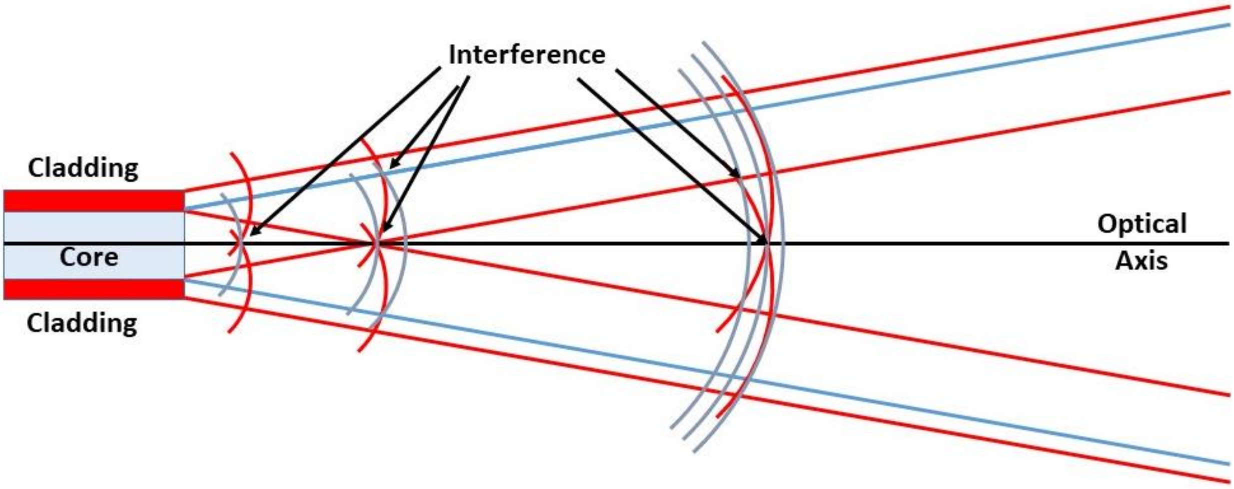

Fig. 2. Illustration of the interference of cladding and core pulses.

3. Experimental setup

In Figure 3 the schematic of the experimental setup can be seen.

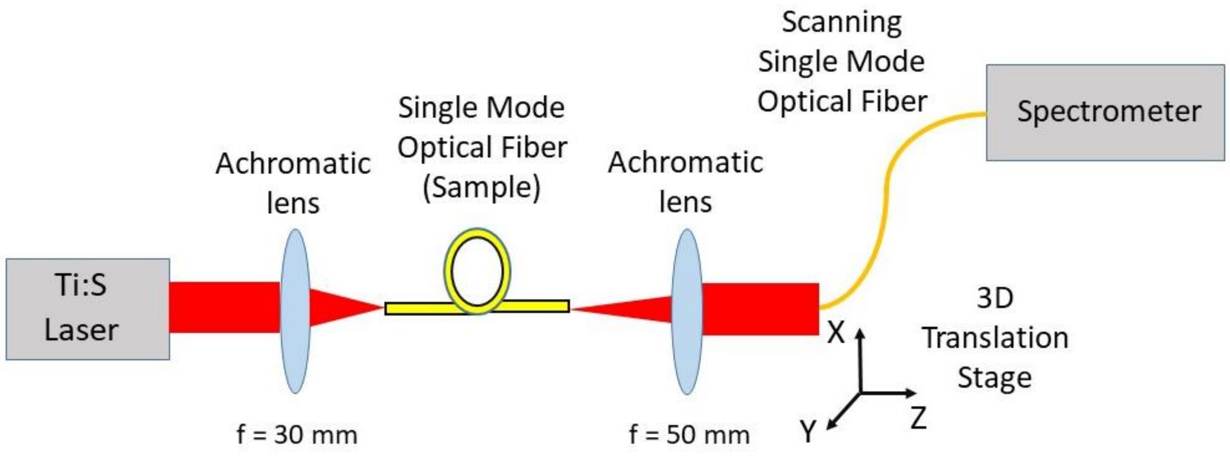

Fig. 3. Experimental setup.

The ultrashort pulses from a Ti:sapphire laser oscillator (6 fs @800 nm) are coupled into a 1-m-long single mode fiber sample using an achromatic lens with a focal length of 30 mm. After propagating through the fiber the beam is collimated with another achromatic lens ($f = 50$ mm). At a given Z distance from the second lens an automated 3D translation stage can be found, which moves a scanning single mode fiber attached to a high- resolution spectrometer. At different X coordinates a cross-scan along the Y axis is made by recording the spectra. This way the collimated beam can be characterized spatially and spectrally.

4. Results

A typical spectrogram recorded along the Y axis after the single mode fiber sample is shown in Figure 4 (a). Performing an IFFT on the recorded spectra one can obtain signals in the time domain (see Figure 4 (b)). When we took a section along the optical axis, multiple peaks were observed as can be seen in Figure 4 (c). To find the signal arising from the cladding pulse, a cross-scan was performed on the laser beam itself without any other optics in the beam's path. After IFFT of the input beam's spectrogram, by taking out the section along the optical axis, we can determine which signal belongs to the laser beam itself and which appears when the sample fiber is put in. In Figure 4 (d) the section along the optical axis of the IFFT signal of the input beam can be seen and there is no peak at around 230 fs. Since the single mode fiber only supports one mode in the core, the peak at 230 fs in Figure 4 (c) can only come from the cladding. Please note that the signal has an X like shape, which is drawn with red dashed lines in Figure 4 (b). This special shape also proves that the signal arises from the cladding. Since a ring-shaped pulse leaves the cladding in angle when it approaches the optical axis, it gets closer to the core pulse and creates an X like shape, as it propagates faster than the core pulse.

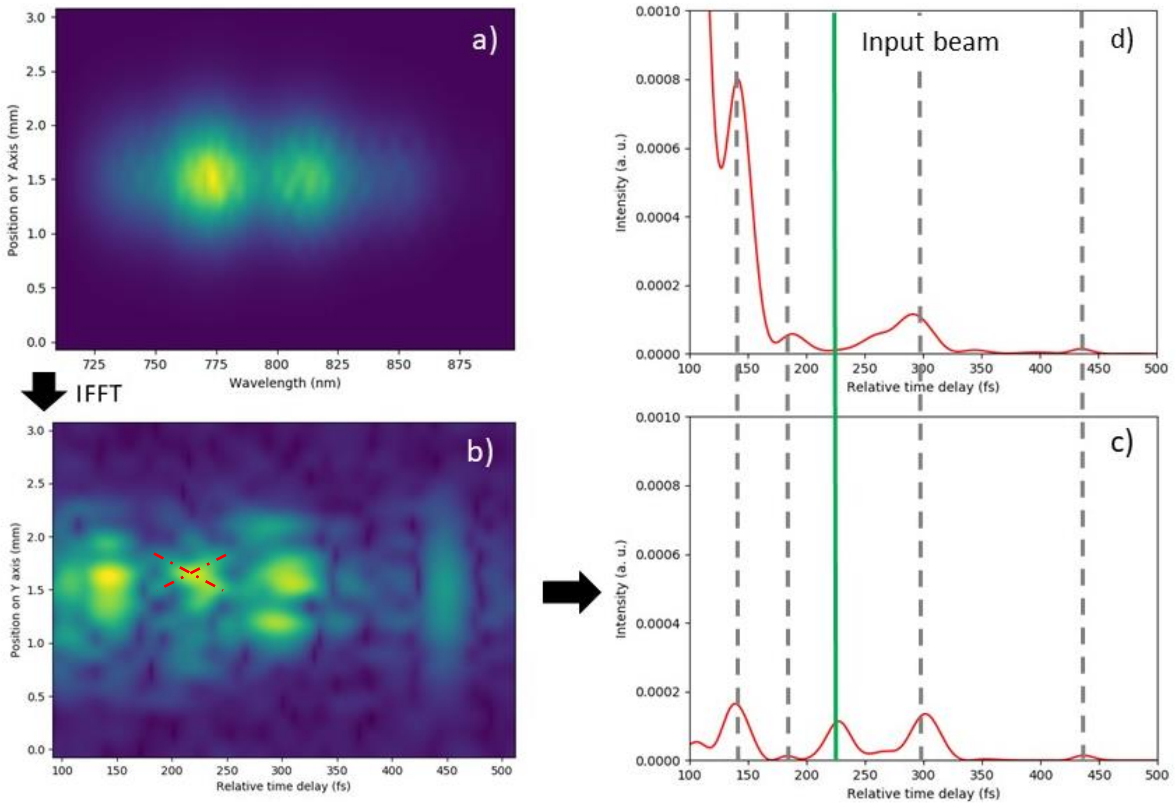

Fig. 4. (a) a typical spectrogram recording after the single mode fiber and (b) its IFFT signal. (c) IFFT signal at the optical axis (section at y = 1.6 mm). (d) IFFT signal of the input beam along the optical axis. Please note that after the fiber an extra peak appears in the IFFT signal at 230 fs.

After finding the peak to be investigated, measurements were carried out with 1 mm steps on the X axis and with 10 µm steps along the Y axis, both in range of 12 mm. To evaluate the measurements, an IFFT was performed on the recorded spectra at each given (x, y) point to obtain information in the time domain. Results of the cross-scans at different X vertical positions are shown in Figures 5-7.

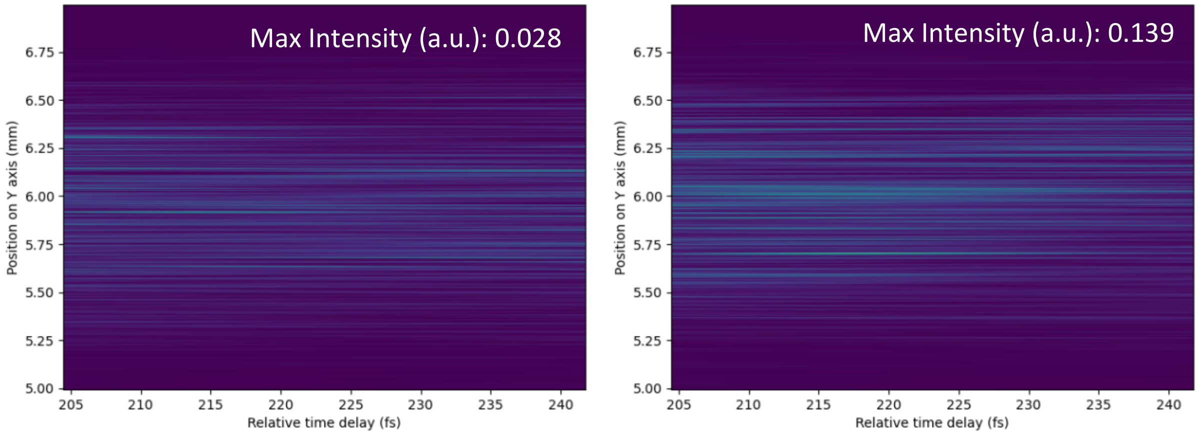

Fig. 5. Spatially resolved IFFT signals at vertical position x = 1 mm (left) and x =3 mm (right).

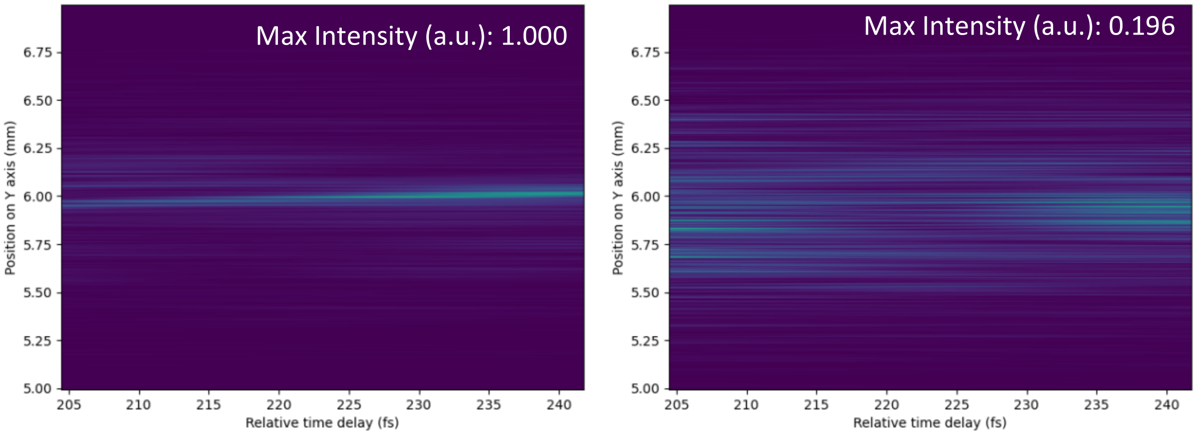

Fig. 6. Spatially resolved IFFT signals at vertical position *x* = 5 mm (left) and *x* = 7 mm (right).

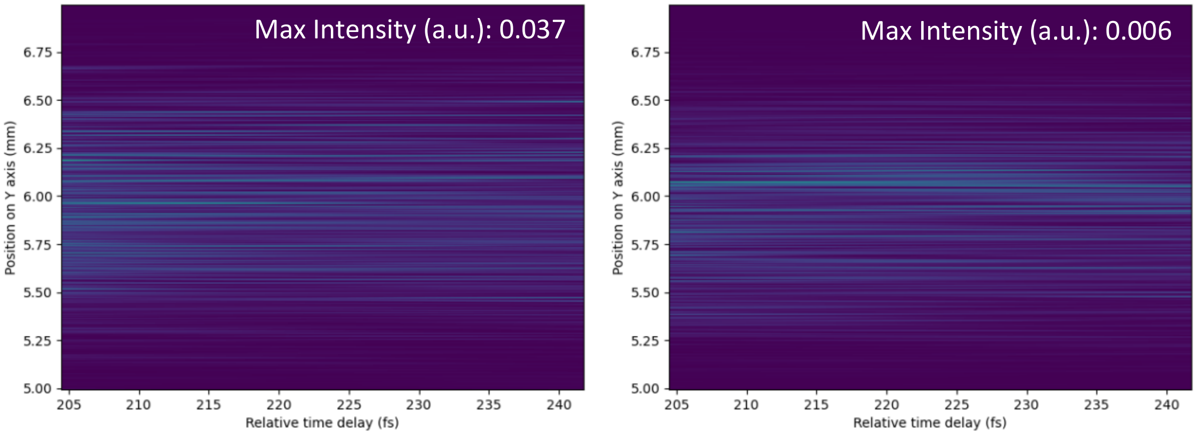

Fig. 7. Spatially resolved IFFT signals at vertical position *x* = 9 mm (left) and *x* = 11 mm (right).

One can see that at *x* = 5 mm a signal appears along the optical axis (*y* = 6 mm), which arises from the interference between the cladding and the core pulses. At the different vertical positions there are no signals present, indicating that the cladding pulse interferes with the core pulse the most intensively on the optical axis, which is due to cylindrical symmetry mentioned in Section 2. Since the colormap can be deceiving, the maximum intensity values are shown in the upper right corner of each picture.

5. Summary

In this work we have presented that ultrashort laser pulses can propagate in the cladding of single mode fibers. Cladding pulses exiting the fiber can interfere with the core pulse, which can be undesirable in experiments or applications. Although we were able to find conclusive evidence, further analysis is required to fully understand and characterize the cladding pulses generated in single mode optical fibers.

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