Advances in Fiber Delivery of Ultrashort Pulses at 800 nm

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ABSTRACT

Latest advances in femtosecond technology have strongly emphasized the control of ultra-short pulses in many applications where the preservation of the pulse duration is most important. Recently, the delivery of ultra-short pulses through optical fibers has become possible which opens up remarkable chances for simplifying optical setups or reaching inaccessible regions. In this study we report on fiber delivery of 2 nJ and sub 65 fs pulses from a Ti:Sapphire laser through 1.5 m LMA photonic crystal fiber. Application of such a fiber in an all-integrated THz imaging system to obtain contactless information on the doping concentration of semiconductor wafers is shown.

Keywords: Fiber delivery, femtosecond laser, dispersion compensation

1. INTRODUCTION

Ultrashort pulses from Ti:Sapphire lasers have found spread applications in the field of spectroscopy, nano-/ micro materials processing or THz generation for instance where the sharp rise in the light electric field or the peak power of the pulse is most important. Recently great interest for fiber delivery for such intense optical pulses emerges since it gives much flexibility for laser integration or allows access to steadily moving or difficult attainable regions. Fiber delivery was successfully shown for three-dimensional high resolution imaging in nonlinear optical microscopy[1]. It also has decisive impact on multiphoton endoscopy and potentially extends the capability of coherent anti-Stokes Raman scattering (CARS) to endoscopic applications[2]. In the field of Terahertz science fiber-coupled THz emitters and receivers were employed for ultrafast coherent spectroscopy for instance[3]. However, short pulses are suffering chromatic dispersion when passing through optical elements while changing their temporal shape. The wavelength dependence of the refractive index of the medium stretches the pulse temporally, thus lowering its peak power. Therefore technological limitations and eligible concerns have always marked preferences for pulses with rather narrow spectral bandwidths which are less susceptible to temporal broadening. Generally, the handling of ultrashort pulses requires a very good understanding of the physics since, e.g. a 50 fs pulse stretches to about 206 fs whereas a 100 fs pulse turns to just 141 fs after 10 cm of fused silica. The quite huge spectral bandwidth of shorter and shorter pulses is the real challenges to their management.

Recent developments have shown remarkable progress in using sub 12 fs pulses for multi-photon applications[4]. Chirped mirrors were shown to be able to compensate a pair of high numerical objectives over a wavelength range of 700 nm to 900 nm. However, delivery of ultrashort pulses through a single mode fiber puts more challenges to both the amount of material dispersion to be compensated and the distortion of the pulse shape due to fiber nonlinearities. 82 fs and 0.4 nJ pulses were sent through altogether 0.75 m single mode fiber by a pulse replica compression technique with prisms by Clark et al[5]. Ouzounov et al. demonstrated 140 fs and 3 nJ pulses travelling through 1.3 m micro-structured large mode area fiber by use of a grating compressor[6]. Without pre-compression Göbel et al. delivered 170 fs pulses through a hollow-core photonic crystal fiber for pulse energies up to 4.6 nJ[7]. Using the large dispersion of a higher order mode Ramachandran et al. sent 0.9 nJ and sub 150 fs through 2 m of a few mode fiber[8]. Luan et al. even described the delivery of 65 nJ and 290 fs pulses from a 5 kHz regenerative amplifier over five meters of hollow-core photonic bandgap fiber by exploiting the effect of soliton pulse propagation[9]. At 1550 nm Omnetto et al. could send 214 fs pulses by using an iterative pulse shaping technique through 10 m conventional single mode fiber[10]. And Nicholson et al. demonstrated the delivery of 152 fs and about 9 nJ pulses in the LP07 mode of a 5 m high order mode fiber which was directly spliced to a Erbium doped fiber amplifier[11]. In this study we report on the delivery of 64 fs and 2 nJ pulses through 1.5 m large mode area (LMA) fiber. This presents to our knowledge the shortest pulses from a conventional Ti:Sapphire laser delivered through a single-mode optical fiber.

2. THEORETICAL BACKGROUND

Laser pulses travelling through optical fibers are not only affected by material dispersion but are also subject to nonlinear effects due to their confinement to the rather small core of the waveguide. Therefore, even moderate pulse peak power can induce nonlinearities since the interaction length is essentially given by the length of the fiber. Fortunately in conventional silica core fibers this effect is rapidly mitigated by the fact that dispersion is stretching the pulse and thus limiting the interaction length for nonlinear effects. This suppression of nonlinearity was for instance demonstrated by exploiting the much higher dispersion of higher transversal mode of a non-single-mode fiber[8]. Here the pulse will not travel a large enough distance with high peak power to experience significant nonlinear pulse distortion, hence facilitating higher energy pulse transmission. The propagation of pulses through a fiber is usually described by two parameters called the non-linear length L_{NL} and the dispersion length L_D[12]

$$L_D = -\frac{2\pi c}{\lambda^2}\frac{\tau^2}{D} \qquad\qquad L_{NL} = \frac{A_{eff}\lambda}{2\pi n_2 P}$$

where D is the fiber dispersion, τ denotes the undistorted pulse duration, λ the center wavelength, A_{eff} the effective area, P is the peak power and n_2 is the nonlinear refractive index. If L_D is much smaller than L_{NL} the pulses are getting linearly stretched or compressed depending on their initial chirp. They see the fiber more or less as a bulk transparent. In contrast, if L_{NL} is shorter than L_D the pulses are suffering spectral broadening or narrowing and lose their capability to exit the fiber with the initial pulse duration. In order to avoid nonlinearities or to keep them as small as possible one has to limit the peak power P to enlarge L_{NL} over L_D. This ensures that the linear stretching happens in a much shorter time scale than nonlinear interactions can essentially evolve. A much better approach, however, which allows more powerful pulse propagation is to increase the effective core diameter, hence A_{eff}.

This approach has been possible in the last recent years with the advent of micro-structured photonic band gap fibers. In terms of fiber based pulse delivery they can be divided into two different categories. In hollow-core photonic band-gap fibers a defect region is created in the photonic band gap structure, thus providing an “extra” air hole where the light can propagate. Due to the virtual absence of nonlinearity these fibers are able to deliver short optical pulses in a single spatial mode at power levels not achievable with conventional fibers[7]. However, they show high attenuation losses and the zero dispersion regime covers just several nanometers at the design wavelength with a large contribution of third order dispersion. The second category refers to the so-called large mode area fibers (LMA). They use a micro-structured cladding to confine light in a pure silica core. This allows large effective mode field areas, even with single-mode operation in the 600 – 1000 nm wavelength range and much lower transmission losses. In the past few years efforts to increase A_{eff} led to the invention of higher-order-mode fibers (HOM, OFS Laboratories). Instead of using the conventional fundamental mode, a certain single higher-order mode is excited with a broadband long period grating before launching into an intentionally few-moded fiber. Depending on the higher order mode excited, effective areas up to 3200 µm² had been achieved. Although fiber delivery of 0.9 nJ-150 fs@800 nm and 9 nJ-152 fs@1550 nm were reported[8,11] we retain further discussion in this paper to pulse propagation in the fundamental mode.

3. EXPERIMENTAL SETUP

We start from a commercial standard Ti:Sapphire laser (Integral, Femtolasers Produktions GmbH) pumped by an all solid-state frequency doubled laser at 532 nm. The whole system is temperature stabilized, completely sealed, with integrated diagnostics and processor controlled power stabilization, enabling maintenance free turn-key operation. The laser delivers up to 300 mW of bandwidth limited 25 fs pulses at a repetition rate of 76 MHz. The layout of the setup is shown in Fig. 1. The beam is directed through an optical isolator to prevent back reflection from the end facet of the fiber. P1 and P4 are LAK16 prisms whereas P2 and P3 are F2 prisms. The mixture of prism material is supposed to give a good compromise between compactness and dispersion compensation since F2 allows a short prism distance while LAK16 introduces very low third order dispersion. Separation between P2 and P3 (~2.5 m) is adjusted to obtain the shortest pulse duration after the fiber, i.e. to compensate the GDD of the isolator, the fiber coupler, beam splitters, the air, and the fiber itself.

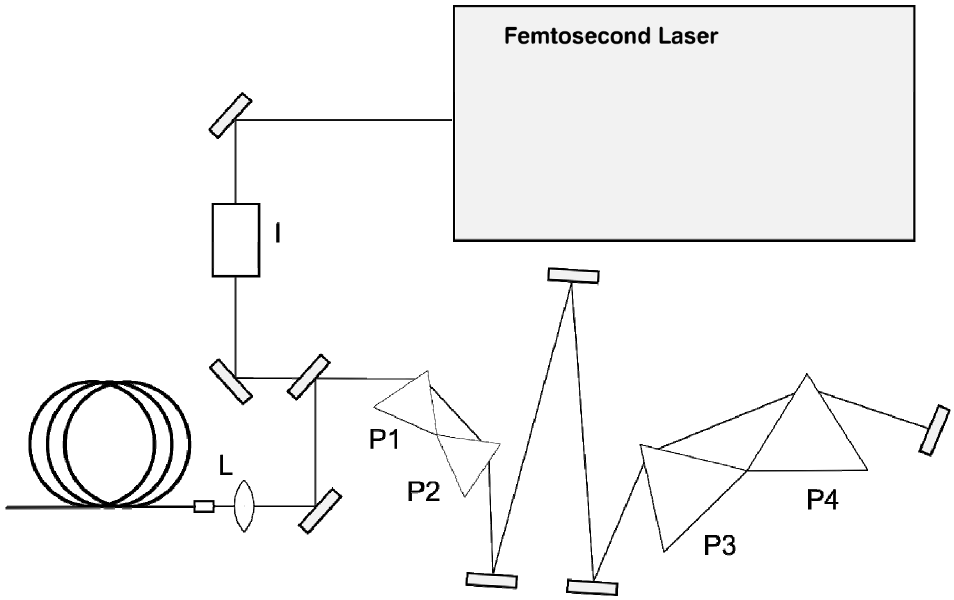


Fig. 1. Experimental setup of the fiber compressor using two double prism pairs.

Latter is a large core polarizing photonic crystal fiber (LMA-PZ-800 from Crystal Fibre) optimized for single-mode operation at 800 nm. The pure silica core has a mode field diameter of about 15.5 µm, thus yielding ~190 µm² effective mode field area. Numerical aperture is given as 0.032 @ 635 nm, and the specified attenuation is as large as <0.015 dB/m for a moderate bending radius of 16 cm. Here we noticed higher bending losses than conventional single-mode fibers although this was not measured in detail. The ends of the fiber are heat treated to close the air holes and inserted into a FC/PC connector before end polishing. The fiber length in this experimental setup is 1.5 m.

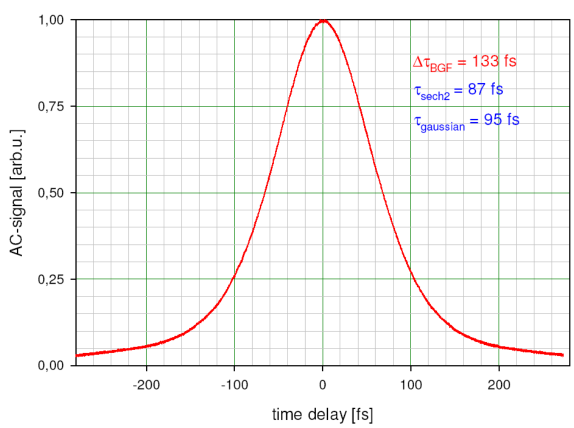


Fig. 2. Non-collinear autocorrelation for grating compensated pulses from the photonic crystal fiber.

4. RESULTS AND DISCUSSION

4.1 Grating compressor

To study possible pulse fiber delivery schemes it is very instructive to investigate different dispersion compensation techniques. Starting with a similar setup as in Fig. 1 the prism sequence is replaced by a pair of gratings. Sub 50 fs pulses from a Ti:S laser are fed through the gratings in double pass configuration and coupled into a 1.6 m long large mode area (LMA) fiber. With an overall efficiency of ~31 % (laser to fiber) 45 mW of 0.5 nJ pulses is delivered through the fiber. Fig. 2 shows a non-collinear autocorrelation measurement of the 87 fs pulses (assuming $sech^2$ pulse shape). Output power through the fiber and pulse energy is mainly limited by the laser at the time of measurement (145 mW). The spectral bandwidth reduces from 19 nm to 10 nm which shows that non-linearity induced spectral narrowing and third order dispersion are mainly responsible for the formation of the temporal envelope. However, this setup is very compact since gratings separation is merely 1.5 cm. The rather high pulse energy and the pulse duration in the 80 fs regime demonstrate the advantage of the LMA fiber over conventional singe-mode fibers.
In contrast, fiber delivery with standard single-mode fibers (Thorlabs SM600, mode field diameter 4.3 µm) reveals emerging self-phase modulation at already 3 mW from 100 fs pulses of the Ti:S laser. As indicated in Fig. 3 the pulse duration is increased to 140 fs once the pulse energy reaches 0.035 nJ and further increases to 156 fs at 0.06 nJ. This represents fairly the limit in terms of pulse energy which can be delivered through a few meters of standard single-mode fiber for pulse duration between 100 and 150 fs.

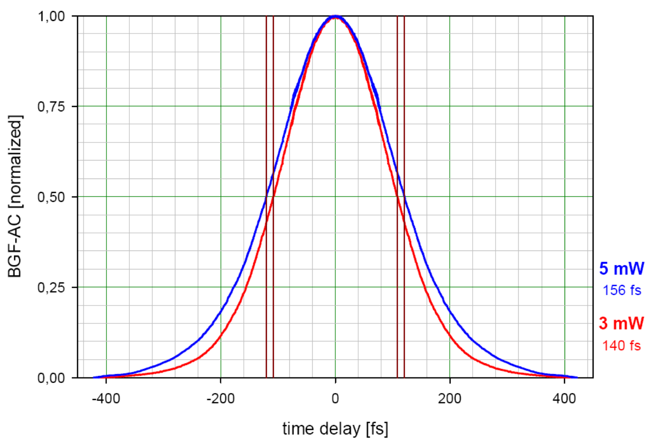


Fig. 3. Non-collinear (background free) autocorrelation for grating compensated pulses from a conventional single-mode fiber.

4.2 Prism compressor

The results from the dispersion compensation by using gratings show that at least 10 times more pulse energy can be delivered through a large core PCF than a conventional single-mode fiber. The pulse duration is mainly limited by nonlinear effects and higher order dispersion of the fiber core medium. Although gratings efficiently compensate GDD they introduce very large third order dispersion (TOD) which has unfortunately the same sign like the TOD of the fiber and is almost three times higher, respectively, i.e. in our case. Therefore the use of prisms for dispersion compensation is theoretically more effective to minimize the contribution of TOD. In contrast to gratings prism compressors show negative TOD, thus potentially cancelling the TOD from the fiber. However, they are showing quite the same absolute amount of TOD like gratings and therefore more than compensate the fiber's TOD. Table 1 contains the second and third order dispersion of different components. They are calculated to compensate the second order dispersion of the fiber, thus allow comparing the net residual TOD numbers for the prism and grating compressor.

Table 1 Comparison of dispersion contribution of different components and their combined net TOD.

	GDD [fs²]	TOD [fs³]
Fiber [1.5 m]	+ 54 170	+ 41 160
Grating pair	- 54 170	+ 109 600
Double prism pair [LAK16]	- 54 170	- 102 000
Double prism pair [F2]	- 54 170	- 130 000
Fiber + Grating pair	0	+ 150 760
Fiber + Prism pair [LAK16]	0	- 60 840
Fiber + Prism pair [F2]	0	- 88 840

Table 1 illustrates the advantage of using a prism compressor in terms of uncompensated TOD. Here LAK16 offers lower residual TOD than F2 which is about one third of the absolute TOD for gratings. In our experiment the combined double prism scheme (LAK16 and F2 at the same time) gives a slightly more compact setup than with LAK16 prisms only which results in net TOD of about -75800 fs³.

Laser light as much as 300 mW average power with spectral bandwidth of about 40 nm is pre-compressed by above described prism compressor scheme and coupled into 1.5 m LMA fiber. A 75 mm lens is used matching the beam size of about 8 mm with the NA of the photonic crystal fiber. Coupling efficiency was 68 % and the largest average power through the fiber was 155 mW. This corresponds to ~2 nJ pulse energy and ~32 kW peak power. At this power level the spectral bandwidth reduces from initially 40 nm to just 20 nm due to fiber nonlinearities, and the pulse duration was 64 fs deduced from a fringe resolved autocorrelation measurement. This represents the shortest pulses from a Ti:S laser one can expect for a fiber delivery. However, the residual contribution of TOD can be seen from the shape of the autocorrelation trace, i.e. it still limits the level of pulse compression. Fig. 5 shows the autocorrelation measurement and Fig. 4 depicts the many light spectra at different average power inside the fiber. A steady narrowing of the spectral bandwidth from both the short and the long wavelength side continues with increasing intensity.

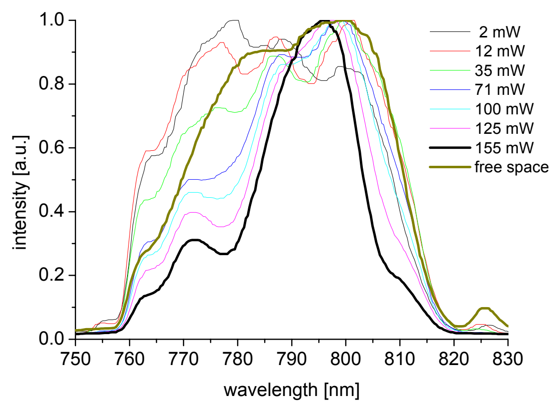


Fig. 4. Prism compressor: Spectra of the laser light at different average output power in the fiber.

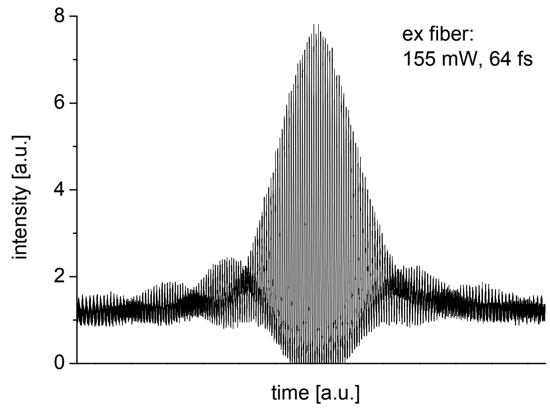


Fig. 5. Prism compressor: Pulse duration in the case of 155 mW average power coupled into the fiber.

Interestingly below 12 mW the spectral bandwidth increases accompanied by a pronounced spectral modulation. This effect is probably due to Raman scattering since it exists even at lowest peak power where nonlinearities should be negligible. This could also be the reason for the initial spectral broadening. But also at highest average and peak power Raman scattering can be the cause for the asymmetric spectral forming and narrowing. The evolution of the spectral bandwidth, defined as a FWHM of the spectral intensity, is shown in Fig. 6. Initial 40 nm FWHM from the laser increases first to about 50 nm and decreases continuously to 20 nm at 64 mW. The corresponding evolution of the pulse duration is plotted in Fig. 7. Within the recorded region the pulse duration is reduced at a rate of roughly 1 fs / 6 mW. Below 60 mW the pulse duration is even less than 50 fs. Compared to 45 mW and 87 fs obtained with the grating compressor the distinct improvement is referred to the much lower residual TOD.

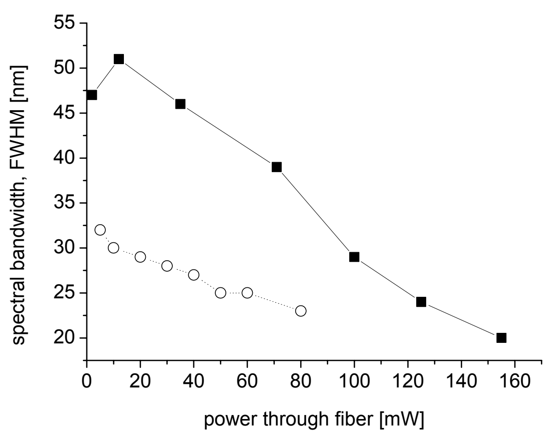


Fig. 6. Prism compressor: Evolution of spectral bandwidth with increasing fiber output. Circles indicate the evolution of 33 nm pulses.

The overall tendency indicates a strong spectral narrowing once the pulse peak power is becoming relevant for nonlinearities. But despite additional broadening from remaining TOD, pulses at the end of the fiber are likely to be shorter if there is more spectral bandwidth from the laser available. This is also observed for an initial bandwidth of 33 nm. The evolution of the spectral bandwidth is shown in Fig. 6. Once the average power reaches 80 mW about 35 nm is left from the 40 nm pulse, but less than 25 nm remains from an initial 33 nm. Although not plotted the autocorrelation reveals 64 fs at 80 mW instead of 53 fs for the 40 nm pulse. This indicates that spectral narrowing dominates over TOD in the pulse formation. It could be interesting to further investigate how larger spectral bandwidths than 40 nm affect the final pulse duration after the fiber. However, if the spectral bandwidth becomes too large TOD might prevail and invert the advantage of a broader spectral bandwidth.

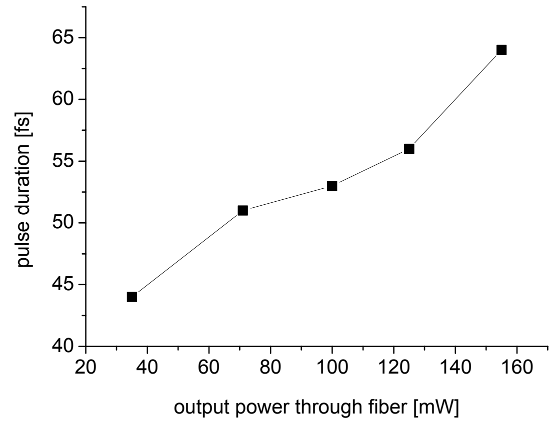


Fig. 7. Prism compressor: Evolution of the pulse duration with increasing fiber output.

4.3 Prism & chirped mirror compressor

Although application of prisms for alienating the residual TOD has led to remarkable results there is still motivation for femtosecond laser pulse delivery in the 100 mW range with pulse durations even less than 50 fs. As discussed above limitations with respect to fiber nonlinearity and higher order dispersion pose the main restrictions. The TOD of the prism compressor acts against the TOD of the fiber but also overcompensates to several -10,000 fs³ (see Table 1). Therefore the remaining third order dispersion has to be removed in order to go below the sub 60 fs pulse duration limit for the fiber delivery.

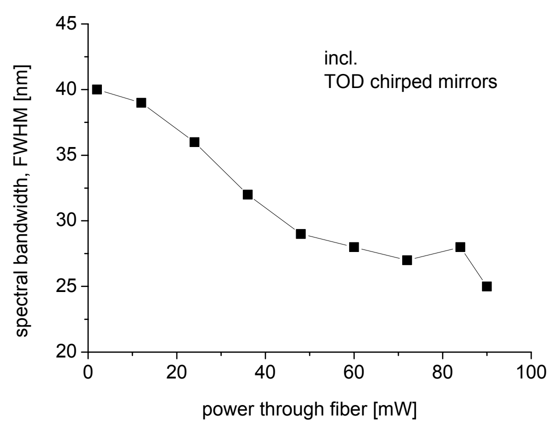


Fig. 8. Prism and chirped mirror compressor: Spectral narrowing induced by fiber nonlinearities.

To do so we inserted third order dispersion mirrors in front of the optical isolator (in Fig. 1). One pair of TOD mirrors was used with 13 bounces on each resulting in 52 bounces and about +62,000 fs^3 of dispersion in summary. Due to higher losses from both the reflections on the TOD mirrors and the increased beam size the maximum average power in the fiber was limited to 96 mW. Results for the spectral bandwidth and the corresponding pulse durations are shown in Fig. 8 and Fig. 9. Compared to the case without TOD mirrors the spectral bandwidth does not increase in the first 10 mW range since spectral narrowing might already prevail over Raman scattering. This has to be discussed and confirmed in detail. At the same time the spectral narrowing gets more pronounced leading to less than 25 nm bandwidth at 90 mW. It is noticeable that without the chirped mirrors this was not observed (see Fig. 6). Despite the narrower bandwidth at 90 mW the pulse duration turns out to be less than 50 fs. With decreasing power it shortens at a comparable rate of about 1 fs / 6.6 mW and drops below 40 fs at 40 mW. Measurement of 48 fs at 90 mW is shown in Fig. 10. The measurement of the shortest pulse duration is shown in Fig. 12 which is 38 fs at 24 mW. Applying the rate of change for the pulse duration over the average power the pulse duration for 100 mW is expected to be 49.5 fs. In general, both the increase of spectral narrowing and the distinct shorter pulse duration are referred to the improved TOD management.

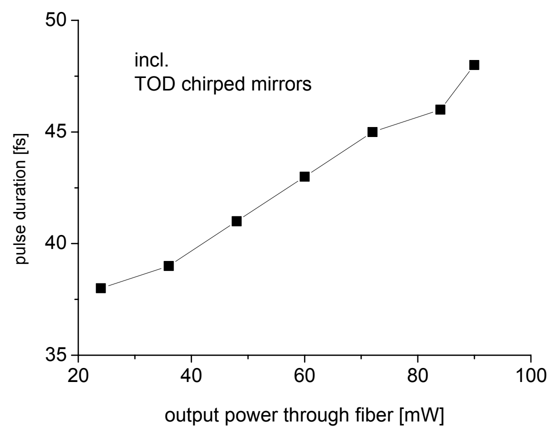


Fig. 9. Prism and chirped mirror compressor: Pulse duration vs. fiber output.

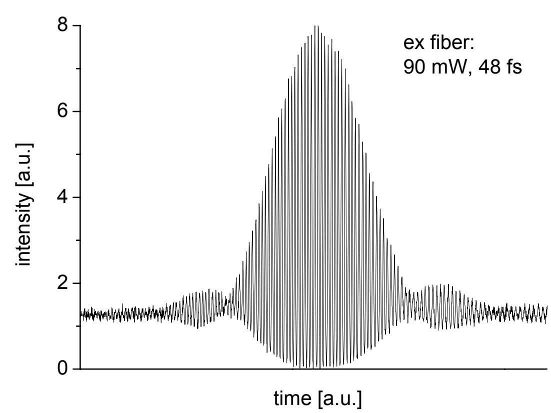
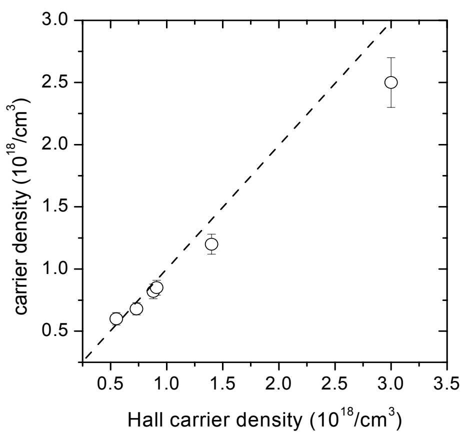


Fig. 10. Prism and chirped mirror compressor: Fringe resolved autocorrelation of TOD compensated 1.2 nJ pulses through 1.5 m fiber.

5. APPLICATION OF ULTRASHORT PULSE DELIVERY TO THZ SENSING

The fiber delivery of ultrashort NIR pulses can be exploited with great advantage in an optical system which contains movable parts. This is the case for a terahertz time-domain spectroscopy system[13]. Such system uses a gated detection scheme and therefore the optical length of both terahertz probe path and NIR gating beam path has to be kept constant whenever the configuration is being modified. Especially important is the fiber delivery in the ellipsometry setup. The setup can be configured with a fixed light source and adjustable sample and detector units according to the chosen angle of reflection.

The THz ellipsometry with fiber delivery for gating NIR pulse to the detector unit has been demonstrated on highly doped epitaxial layers of n-GaAs grown by molecular beam epitaxy technique. The highly doped layers exhibit very high reflectivity and very weak frequency dependence on optical parameters. The increase in the conductivity, however, brings an easy measurable change in the phase shift between p- and s-polarized components of THz waves. The set of samples with n-GaAs layers doped between $5x10^{17}$ and $3x10^{18}$ cm^{-3} was first measured in the standard Hall effect set-up. The second set of measurements was performed in the THz ellipsometric system in a configuration with a ‘rotating’ polarizer. The obtained results are shown in the Fig. 11(a), we plot them with respect to the doping data obtained form the Hall effect measurement (sensitive to the density of the free carriers). The standard measurement fails to distinguish the different layers, while the ellipsometry keeps enough sensitivity even for the heavily doped layers. In addition, we have performed similar set of measurements on semiconductor heterostructures containing a 2-dimensional electron gas.



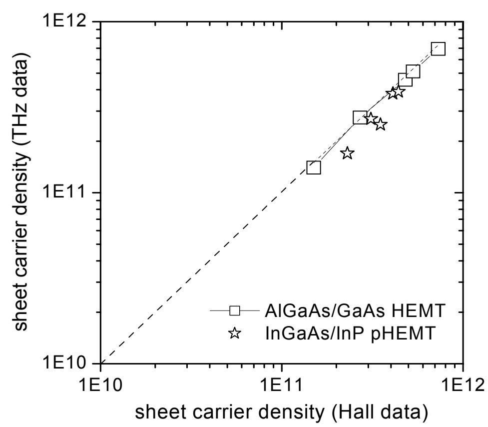


Fig. 11. Assessment of (a) the highly doped epitaxial layer, (b) two dimensional electron gas in a HEMT heterostructure. Data obtained by THz ellipsometry are compared to Hall data.

6. SUMMARY AND OUTLOOK

The route to fiber delivery of sub 50 fs pulses from a Ti:Sapphire laser is described which facilitates a plethora of novel applications in imaging and spectroscopy with ultrashort pulses. Gratings compressors offer compact solutions for sub 100 fs pulses but are essentially limited by higher order dispersion which, among nonlinearity induced spectral narrowing, puts the most stringent limitation to shorter pulse durations. In contrast, a prism compressor facilitates 64 fs pulses at 2 nJ (155 mW, 76 MHz) travelling through 1.5 m of single-mode photonic crystal fiber. By combining prisms and dispersive mirrors even 48 fs @1.2 nJ are possible corresponding to 90 mW average power through the fiber. Moreover this study reveals that fiber delivery in the sub 100 fs and 1 nJ range requires a sufficient initial spectral bandwidth to compensate nonlinearity induced spectral narrowing. At less optical power (i.e. 24 mW and 0.3 nJ), thus less nonlinearity, we have demonstrated 38 fs which to our knowledge represents the shortest pulses (@800 nm) ever delivered through >1 m fiber. Future investigations might be directed to novel chirped mirrors which compensate both second and third order dispersion at the same time. However, such mirrors are challenged by the spectral bandwidth that is necessary to obtain the shortest possible pulses. At last we have shown that the delivery of femtosecond laser pulses through a fiber is a promising and convenient tool for THz sensing applications.

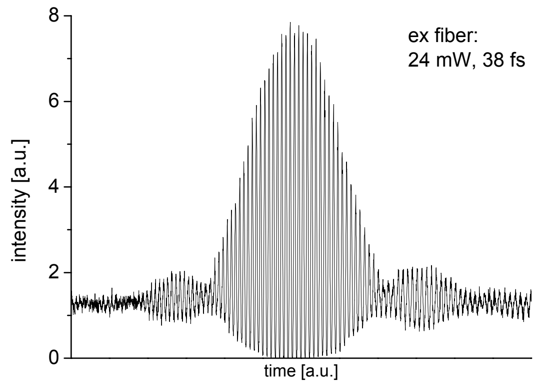


Fig. 12. Prism and chirped mirror compressor. Autocorrelation of the shortest pulses sent through 1.5 m SM fiber. The pulse energy is 0.3 nJ.

Acknowledgement

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