Generation of Femtosecond Pulses in 1 µm Spectral Range by Dispersion Managment with Asymptotically Single-mode Hybrid Fiber

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Abstract: A novel technique for suppression of unwanted modes in the hybrid fiber with anomalous dispersion near 1 µm has been proposed and realized. For this aim a special absorbing layer was placed to the position of the hybrid mode electric field minimum. As a result all other mode has excessive loss in the spectral region near 1.06 µm. On the contrary the optical loss of the hybrid mode almost does not change. Realized fiber was used for high quality pulse compression down to duration of 440 fs and energy of about of 20 pJ. Intra-cavity dispersion management has allowed us to realize a master-oscillator with output pulse energy up to 0.55 nJ and pulse duration below 700 fs.

1 INTRODUCTION

Intra- or extra-cavity dispersion management is essential demand for femtosecond fiber lasers. The lack of commercially available fibers with anomalous dispersion in the 1 µm spectral region requires utilization of bulk elements (diffraction grating (for example, Okhotnikov, 2003)) for dispersion compensation, which degrade system reliability. To keep monolithic laser design specialty fibers with anomalous dispersion in this spectral region has been intensively developed. However by now all the proposed fiber designs have significant drawbacks: high nonlinearity (in the case of Photonic Cristal Fibers (Monro, 1999; Akowuah, 2009; Herda, 2008; Knight, 2000; Lim, 2002)), few-mode propagation regime (in the case of hollow-core fibers (Lim, 2004; Kolyadin, 2015; Saitoh, 2009; Bouwmans, 2003)), sensitivity to temperature and fiber tension (in the case of high order modes excitation by long-period gratings (Nicholson, 2007; Ramachandran, 2006)). Sophisticated production technology for all these types of fibers, difficulties with splicing to ordinary fibers (Herda, 2008; Knight, 2000; Lim, 2002; Lim, 2004) and limited operation bandwidth (Likhachev, 2007; Luan, 2004; Isomäki, 2006; Z. Várallyay, 2009; Kibler, 2009) prevent wide spreading of above mentioned fiber designs. In the current communication we have proposed a new type of fiber for dispersion management that is free from above mention drawbacks. Utilization of this fiber allowed us to generate high energy femtosecond pulses near 1.06 µm in different laser schemes.

In our previous work a novel hybrid fiber design was proposed (Aleshkina, 2013). Refractive index profile (RIP) of the structure consists of the core with refractive index higher than that of undoped silica. It is surrounded by one or few high-index ring layers, thin depressed layer and undoped silica outer cladding. From general point of view such fiber is a multimode. However, the majority of the fiber modes (including the fundamental one) are localized inside the high index ring layers. There is only one mode, which we call hybrid, located in the core region. The mode electrical field distribution is similar to that of the Bragg fiber mode (Likhachev, 2007). Similar to the Bragg fiber the hybrid mode propagates inside the depressed (relative to the high-index layers) core due to coherent Fresnel reflections from high index ring layers. However total internal reflection mechanism allows propagation of the hybrid mode with a low loss (effective refractive index of the hybrid mode is

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higher than that of undoped silica cladding). The main advantage of the hybrid mode is that it has anomalous dispersion in the wavelength region of about 1 μm (Aleshkina, 2013; Aleshkina, 2015). Utilization of the hybrid fiber as a chirped pulse compressor has allowed us to decrease pulse duration from 8 ps to 330 fs, energy of the pulses was about 0.005 nJ (Aleshkina, 2013).

An additional advantage of the hybrid fiber is possibility of its splicing with a conventional step-index single-mode fiber having a similar mode field diameter. However, a small fraction (~ 10-20%) of the modes localized in the high index ring layers is also excited in this case. The propagation of several modes in the core has not allowed us to realize the truly single mode operation regime of the fiber used as chirped pulse compressor. The autocorrelation traces had several peaks with different intensity, moving away from the central peak when fiber length was increased. Thus an important step for development of lasers based on hybrid fiber design is the removal of unwanted modes from the hybrid fiber.

In the present paper, the method of unwanted modes suppression in the hybrid fiber is experimentally demonstrated. The realized optical fiber was used as a chirped pulse fiber compressor, as well as intracavity dispersion compensation element of ring soliton laser. In both cases subpicosecond pulses with Gauss shape were demonstrated. Study of autocorrelation traces confirms single-mode propagation regime of the hybrid fiber.

2 DESIGN OF THE HYBRID FIBER, FABRICATION AND CHARACTERISTICS

The main idea of the proposed method is based on introduction of a highly absorbing cylindrical layer to the position of operating mode minimum. In this case, the optical loss of the hybrid mode is kept almost unchanged, while the optical loss of the all other (unwanted) modes can be made very high. The reason is that the fraction of unwanted modes power confined in the absorbing layer is orders of magnitude higher as compared to that of the hybrid mode. Figure 1a shows a designed RIP of the hybrid fiber. Calculated dispersion at a wavelength of 1.06 μm is about 100 ps/(nm km) (Figure 1b). The electrical field intensity distributions over the radius for the hybrid mode LP$_{03}$ and modes LP$_{01}$ and LP$_{02}$ located in the high index ring layers are shows in Figure 1a as well. It can be seen that the hybrid mode LP$_{03}$ has two intensity minima, one located inside the fiber core (on the boundary with high-index ring layer), and the second one located between the high-index ring layers (Figure 2a). According to our calculations optical minimum located between the high index ring layers is less sensitive to bending, as well as to shift the operating wavelength. Therefore, from a practical point of view, introduction of the absorbing layer to this position is more preferable. To achieve high optical loss we used doping of the layer with Sm^{3+} ion due to its intense absorption bands in the spectral region near 1 micron.

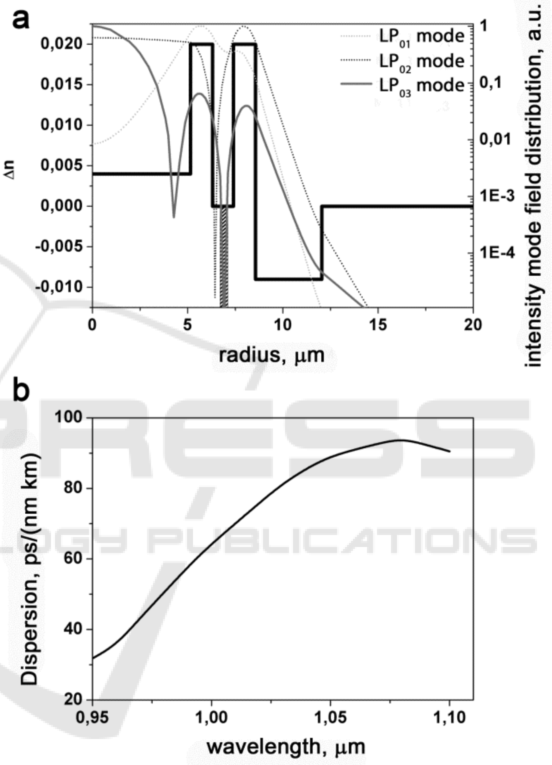

Figure 1: a – Designed refractive index profile of the hybrid fiber and calculated mode field intensity distribution; b – calculated dispersion of the fiber.

The fiber preform was fabricated by the Modified Chemical Vapour deposition (MCVD) technique. The RIP was formed by geranium oxide doping of silica glass. The absorbing layer is implemented by solution doping method. Fiber with an external diameter of 125 μm was drawn from this perform and coated by high refractive-index (n~1.52) acrylate coating. Measured RIP and image of the fiber end are shown in Figure 2. Estimated from prefom analysis Sm ions distribution across the fiber cross section is shown in Figure 2 as well.

Investigation of modal content in the realized hybrid fiber has showed that after 5 m the only one hybrid LP_{03} mode can propagates. Unwanted modes were detected only at fiber lengths shorter than 5m by displacement of the excitation beam from the fiber axis. Even in this case the preferable excitation of the hybrid mode is possible by co-axial splicing. The estimated hybrid mode field diameter was 5.4 microns. The loss spectrum of the hybrid mode is shown in Figure 3. Estimation loss of unwanted modes exceed 14 dB/m. Splicing losses of the hybrid fiber and standard singlemode step index fiber (core and cladding diameter of 6 and 125 microns, correspondingly) at a wavelength of 1.06 μm were 2.5 dB. The dispersion measured in 0.5 m of the hybrid fiber (Hen-Tai Shang, 1981) is shown in Figure 4. Inaccuracy of measurements is associated with a small operating spectral range of the hybrid fiber (~ 100 nm). This spectral region is limited by appearance of high order hybrid modes at short wavelength and cut-off of the hybrid mode in the longer wavelength.

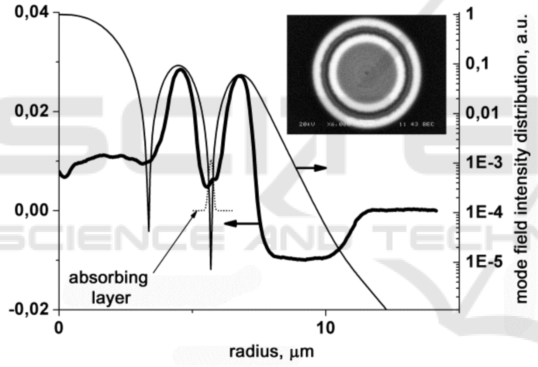

Figure 2: Measured RIP of the hybrid fiber, evaluated mode field distribution of the hybrid mode and distribution of the Sm^{3+} ions across the fiber cross-section. On the inset the image of the fiber end obtained by Scanning Electron Microscopy.

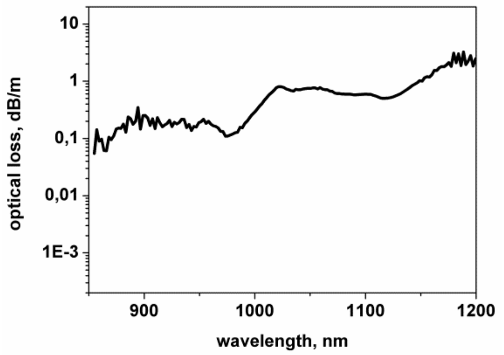

Figure 3: Measured optical loss of the hybrid fiber.

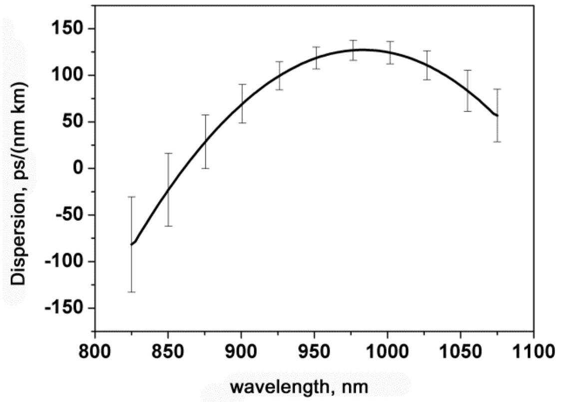

Figure 4: Measured dispersion of the hybrid fiber.

3 COMPRESSION OF CHIRPED PULSES WITH THE HYBRID FIBER

First of all, the fabricated hybrid fiber was tested as a chirped pulse compressor (similar to our previous work (Aleshkina, 2013)). For this aim the master oscillator was realized on the base of Semiconductor Saturable Absorbing Mirror (SESAM) and passive nonlinear optical loop mirror (scheme is depicted in Figure 5). Multimode semiconductor pump diode emitting at a wavelength of 976 nm was used as the pump source. The pump radiation was launched in the scheme with a help of 2+1-to-1 pump and signal combiner. The Yb-doped fiber with cladding absorption at pump wavelength about 8 dB/m was used as the active fiber. The length of the active fiber in the system was 3 m. The Yb-doped fiber core was approximately 10 μm, so a special mode field adapter was fabricated to match the active fiber and other passive fibers (core D~ 6 μm) used in the laser scheme. The amplified signal from the active fiber was couples to a passive nonlinear optical loop mirror (NOLM) formed by 3 m of standard passive fiber (similar to Corning HI1064) together with 30/70 coupler. A similar coupler was used to extract 70% of the propagated signal outside the cavity and reflect 30% back with a help of SESAM. To ensure unidirectional propagation inside the laser system, each tail of the couplers were spliced with isolator. Polarization controller was used to adjust polarization state of irradiation inside the laser. The total cavity length was about 10 m.

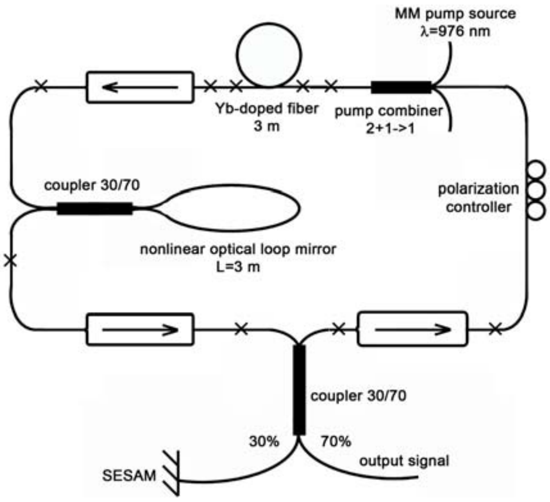

Figure 5: Chirped pulse oscillator scheme.

Mode-locking regime was achieved at pump power of about 450 mW. The average output signal power was 10 mW, the repetition frequency was 20.85 MHz. Typical dissipative solitons with spectral width of about 11.8 nm was observed in this case (Figure 6). Femtochrome Research Inc FR-103 mn autocorrelator with fiber input was used to measure the pulse duration in our experiments. The laser system was polarization-insensitive. By this reason an additional polarization controller based on a standard optical step index fiber with length of 0.4 m was places between the laser and autocorrelator. Pulse width after the master oscillator was estimated to be about 7 ps (inset of Figure 6).

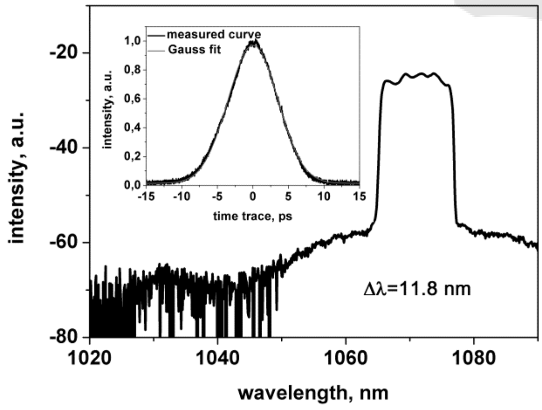

Figure 6: The measured spectrum and time trace of the master oscillator.

To carry out the pulse compression, the realized hybrid fiber was placed between the output end of the laser and input fiber end of polarization controller delivering laser emittion to autocorrelator. The Figure 7 and Figure 8 show dependence of the pulse duration on hybrid fiber length. It is important to emphasize that even when hybrid fiber length was about 3 m the autocorrelation traces had Gauss shape. No additional intensity peaks were observed in autocorrelation trace that indicated absence of the unwanted modes in the system. Only with 1 m of the hybrid fiber a slight broadening of the autocorrelation function was observed, that we associate with excitation of undesirable ring modes.

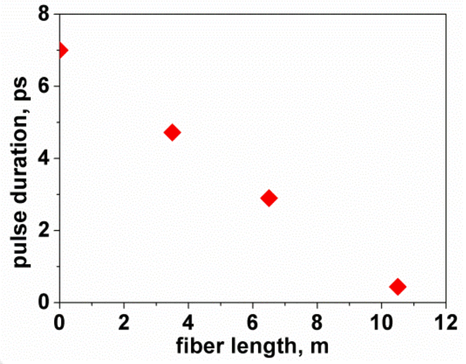

Figure 7: Dependence of pulse duration on length of the hybrid fiber.

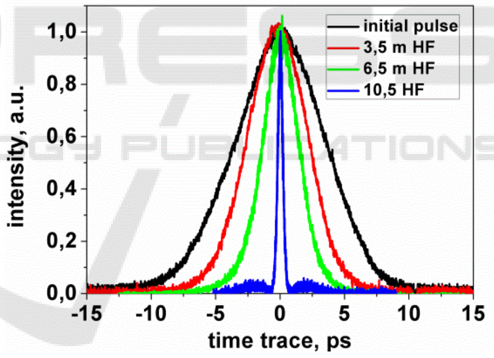

Figure 8: Measured time traces of the pulses after hybrid fiber.

When length of the hybrid fiber was equal to 10.5 m the maximum pulse compression down to duration of 440 fs was observed. The average output power was 430 μW. The signal was decreased by an order of magnitude due to two splices of hybrid fiber with standard single-mode fiber (~ 5 dB net) and intrinsic hybrid mode loss (8 dB for the 10.5 m fiber length). The energy in the pulse was 0.021 nJ. Taking into consideration additional standard fiber at the output of the laser (used in the polarization controller, input of autocorrelator, etc) the hybrid fiber dispersion at the wavelength of 1.06 μm was estimated to be 63 ps/(nm km). No nonlinear effects were registered in the hybrid optical fiber. We suggest that it is coursed by relatively large mode field diameter of the realized hybrid fiber and relatively low electrical field intensity.

The hybrid fiber was also used for intracavity dispersion compensation in soliton laser. Laser scheme is shown in Figure 9. The length of the hybrid fiber inside the cavity was 6.5 m. Solitons with pulse duration as short as 700 fs were obtained at the output of the source. Typical spectra with Kelly's peaks and the autocorrelation function of the output signal are shown in Figure 10 and Figure 11. Time-bandwidth product of Gaussian shaped pulses was equal to 0.48. Output power was 8.6 mW, the repetition frequency was 15.75 MHz, the pulse energy was 0.55 nJ.

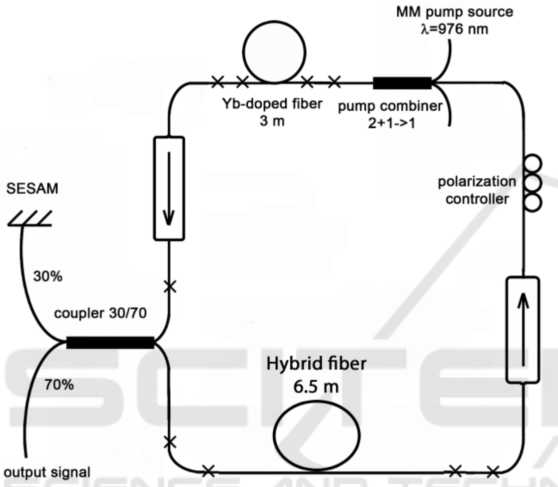

Figure 9: Schematic of the mode-locked soliton laser cavity.

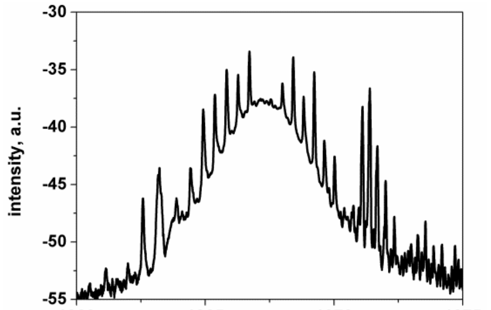

Figure 10: Registered spectrum on the output of the soliton laser.

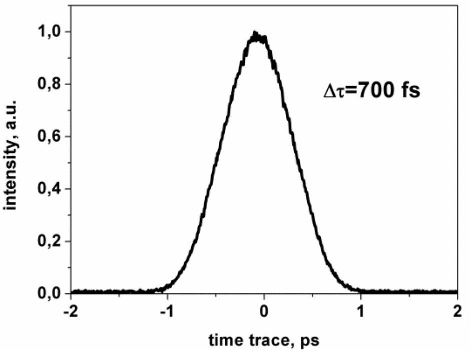

Figure 11: Registered time trace of the soliton laser.

4 CONCLUSIONS

Single-mode propagation regime of the hybrid fiber with selective mode suppression was demonstrated on the example of all-fiber chirped pulse compressor. The usage of the hybrid fiber with length of 10.5 m allowed us to compress pulses with duration of 7 ps to 440 fs without deterioration of pulse shape and quality. The use of the same hybrid fiber in the soliton laser scheme has allowed us to realize stable pulse lasing with soliton energy of 0.55 nJ and a peak power of 850 watts

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