Highly nonlinear fibers for very wideband supercontinuum generation

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ABSTRACT

Supercontinuum generation in highly nonlinear fibers (HNLF) pumped with femtosecond pulses is an area of large interest for applications such as broad band light sources, tunable femtosecond sources, frequency metrology, and fluorescence microscopy. In the last few years, a lot of focus has been put on optimizing photonics crystal fibers for supercontinuum application. In this paper, we will focus on conventional silica based HNLF, which e.g. have the advantage of precise dispersion control, and easy splicing to standard single mode fibers.

We have performed a systematic experimental study of the effect of dispersion, of the HNLF as well as the input power to the HNLF. To pump the fiber we have build an femtosecond fiber laser consisting of a passive mode locked figure eight oscillator followed by an amplifier. The dispersion before coupling into the HNLF was optimized for broadest supercontinuum generation. Supercontinuum generation in both standard and polarization maintaining HNLF are studied.

Keywords: Highly nonlinear fiber, supercontinuum, fiber laser, femtosecond laser, dispersion, polarization maintaining fiber.

1. INTRODUCTION

Supercontinuum generation in highly nonlinear fibers (HNLF) pumped with femtosecond pulses is an area of considerable interest [1, 2]. The applications include broadband light sources, tunable femtosecond sources, frequency metrology, and fluorescence microscopy. In the last few years, several reports on optimizing photonics crystal fibers for supercontinuum application have been published. In this paper, we will however focus on conventional silica based HNLF, which e.g. have the advantage of precise dispersion control, and easy splicing to standard single mode fibers [3].

For efficient supercontinuum generation it is not only important to use a HNLF with a high nonlinear coefficient but also an optimized dispersion profile. We have performed a systematic experimental study of the effect of dispersion of the HNLF. The main focus has been to optimize the bandwidth on the supercontinuum. Due to lack of available equipment to measure the upper edge of the supercontinuum spectra, the main focus has been to decrease the short wavelength edge.

2. CHARATERISTISCS OF HNLF

In this paper the focus will be on conventional solid silica based fibers. Compared to micro structured HNLFs conventional HNLFs have the advantaged of low loss, easy splicing and very precise dispersion control. A disadvantage of conventional HNLFs might be that it is not possible to design fibers with a zero dispersion wavelength much below 1300 nm. However, for supercontinuum generation using pumping at 1550 nm with Er doped femtosecond fiber lasers conventional HNLFs is the preferred choice.

In this work both standard and polarization maintaining (PM) HNLF will be studied.

2.1 Non PM HNLF

The HNLFs were fabricated using the MCVD technique with a design consisting of a high delta core up-doped with GeO_2 surrounded with a depressed region doped by F. By varying the core diameter the dispersion is controlled in a wide region from -10 to +10 ps/(nm·km) at 1550 nm. By varying the width of the depressed region the dispersion slope can be controlled. Two versions where fabricated, a standard version with a dispersion slope at 1550 nm of 0.019 ps/(nm·km) and a dispersion flattened version with a dispersion slope ~0 at 1550 nm. Typical properties of the fabricated fibers are shown in Table 1.

Table 1. Typical parameters for the non PM HNLF tested.

Nonlinear coefficient	$(W\cdot km)^{-1}$	11
Effective area	μm^2	12
Attenuation	dB/km	0.8
Splice loss to SSMF	dB	0.05
Dispersion	ps/(nm·km)	Selected
Dispersion slope	$ps/(nm^2\cdot km)$	0.019 Standard version -0.01 < S < 0.01 Flattened version
Cut off wavelength	nm	1200
PMD	$ps/km^{0.5}$	0.05

2.2 PM-HNLF

PM-HNLF has also been fabricated by the MCVD technique. The fiber design is similar to the standard non PM-HNLF but with an elliptical core to induce birefringence. Typical properties of the fabricated PM HNLF are shown in Table 2

Table 2. Typical parameters for the PM-HNLF tested.

Effective area	μm^2	13
Attenuation	dB/km	0.8
Splice loss to standard Panda PM fiber	dB	0.3
Polarization extension ratio splice to standard PM fiber	dB	22
Dispersion	ps/(nm·km)	Selected
Dispersion slope	$ps/(nm^2\cdot km)$	0.03
Birefringence		0.0002
Cut off wavelength	nm	1300

3. EXPERIMENTAL SETUP

To characterize the supercontinuum performance of the HNLF a femtosecond fiber laser setup as shown in Figure 1 was used as pump source. It consists of a passive mode locked figure eight oscillator followed by an amplifier stage before launching of the femtosecond pulses into the HNLF under test.

The figure 8 oscillator is a passively mode locked laser based on use a nonlinear amplifying loop mirror as saturable absorber [4, 5]. It consists of 2.6 m of Er-doped fiber pumped at 975 nm and 4.7 m of Standard single mode fiber (SSMF), giving a total cavity length of 7.3 m, which results in a repletion rate of 28 MHz. The Er fiber has a 1530 nm absorption of 43 dB/m. The dispersion coefficient at 1550 nm of the Er fiber and SSMF are D = -38 ps/(nm·km) and 17 ps/(nm·km) equivalent to β_2 = 48.4 and -21.7 ps^2/km respectively. The total cavity dispersion is normal (β_2 = 0.020 ps^2).

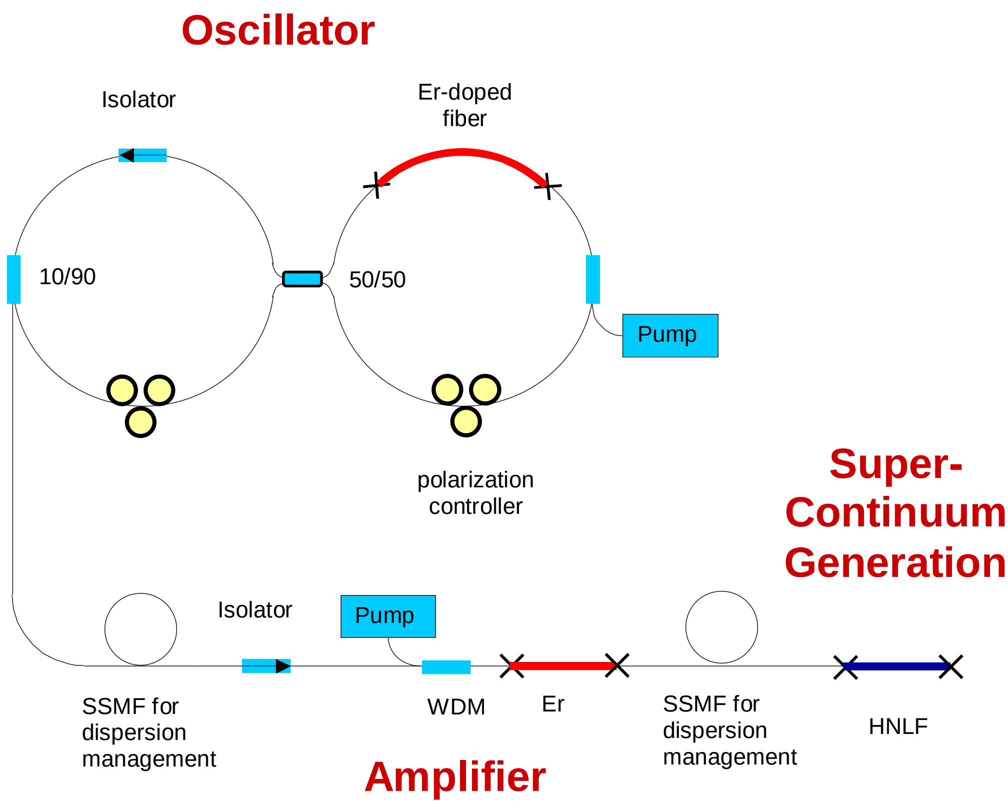


Figure 1. Experimental setup with figure 8 oscillator, and amplifier. Dispersion between stages is managed by length of SSMF.

Using a pump power of 65 mW stable operation with an output power of 1.8 mW is obtained. The output spectrum is shown in Figure 2 left. The 3 dB bandwidth is 32 nm In Figure 2 right, the autocorrelation trace is shown after compression in 3.6 m SSMF, which is the length yielding the shortest pulses. The autocorrelation trace fits well to the trace of a $sech^2$ pulse with a pulse width of 135 fs. The time bandwidth product is 0.52, which is somewhat higher than for a transform limited pulse. Still the pulse quality has been found good enough for supercontinuum generation.

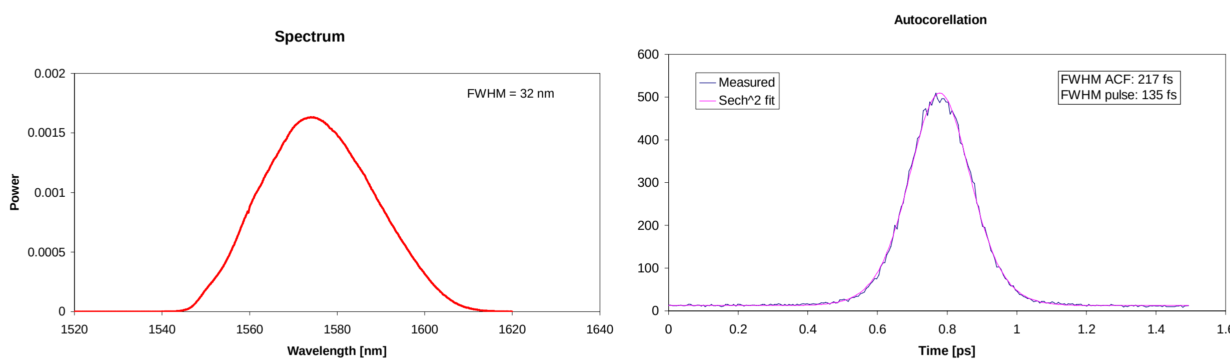


Figure 2. Left: Output spectrum of oscillator. Right: Autocorrelation trace form oscillator after compression in 3.6 m SSMF

The amplifier consist of 2.5 m of Er fiber pumped at 975 nm. The SSMF length between oscillator and amplifier has been optimized for flat output spectrum of the Er-fiber. Due to monitoring taps on the output of the oscillator not shown in Figure 1 the input power to the amplifier is reduced to 0.7 mW. The output power of the amplifier is 150 mW for a

975 nm pump power of 420 mW. In Figure 3 left, the amplifier output spectrum for different length of SSMF after the Er fiber is shown. A significant spectral broadening in the SSMF is observed.

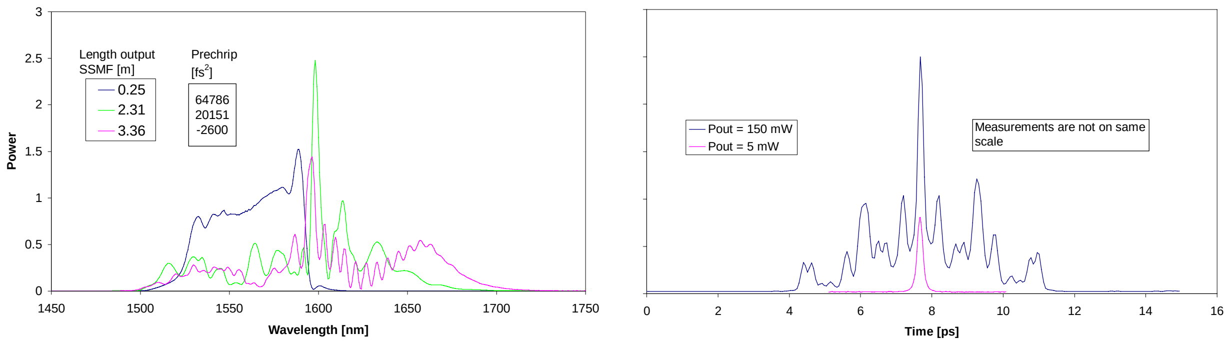


Figure 3. Left: Amplifier output spectrum at 150 mW output power. Right: Amplifier autocorrelator traces after prechirping in 3.24 m SSMF.

In Figure 3 right, autocorrelation traces are shown after propagation in 3.24 m SSMF. Two cases is shown, at max. pumping (output power 150 mW) and a reduced pump power (output power 5 mW). Compression in 3.24 m SSMF gives the shortest pulses at low power pumping of the amplifier. For high gain, a considerable pulse distortion occurs. Still, as evident from the next section, the pulse quality is sufficient to produce a broadband supercontinuum in the following HNLF.

4. SUPERCONTINUUM RESULTS FOR NON PM HNLF

The setup described in the previous section has been used to characterize the supercontinuum performance of various HNLFs with different dispersion characteristics. Before doing so the prechirp before launching into the HNLF has been optimized.

4.1 Optimizing the prechirp

To optimize the prechirp, the length of the SSMF between the end of the Er fiber in the amplifier and the HNLF has been varied. In the previous section it was found that a 3.24 m length of SSFM gave the shortest pulses at low amplifier output power. Therefore a SSMF length of 3.24 m is defined as the length giving zero prechirp. The goal of this optimization is to find the prechirp giving the broadest supercontinuum generation as well to find how much variation in the prechirp can be allowed without affecting the measurement results. The last is important from a practical point of view, as it is very tedious to cut the fiber length with high precession.

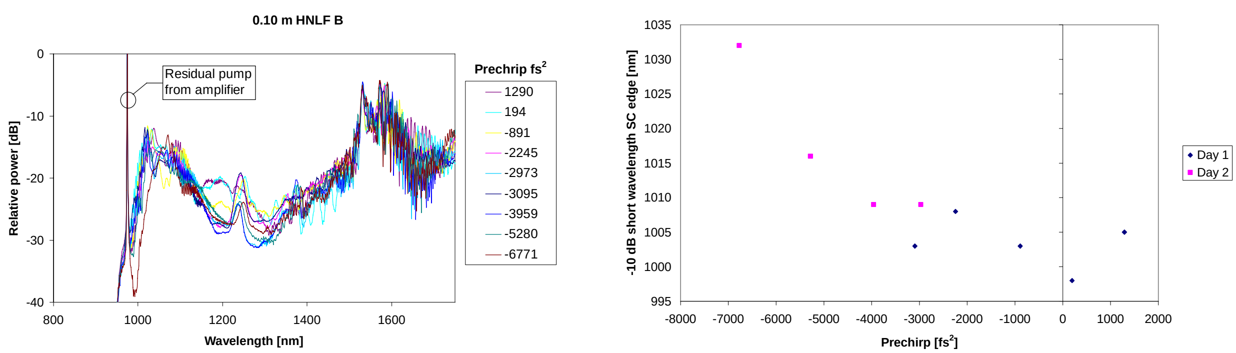


Figure 4. Left: Measured supercontinuum spectra for different prechirp. Right: -10 dB short wavelength supercontinuum edge as a function of prechirp.

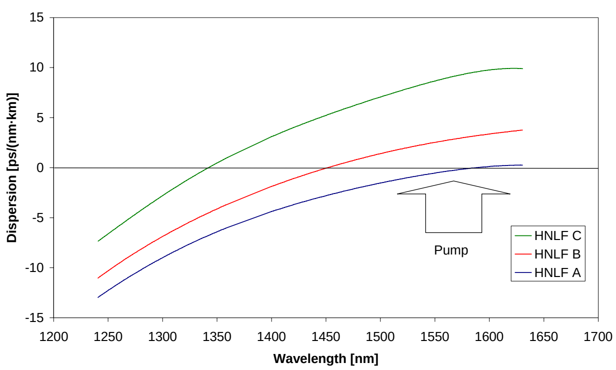
In Figure 4 left, measured supercontinuum spectra are shown for different prechirp. The peak at 975 nm is residual pump from the amplifier. 10 cm of HNLF B was used in this study. The characteristics of the HNLF will be discussed in the next section. The available optical spectrum analyzer unfortunately only allows measurements up to 1750 nm. It is obvious from Figure 4 that the supercontinuum extends much beyond 1750 nm. In this study we will therefore concentrate on the lower supercontinuum edge. As a measure for the broadness of the spectrum, the shortest wavelength where the power is 10 dB lower than the peak power will be used. In Figure 4 right, the short wavelength supercontinuum edge is plotted as a function of the prechirp. Measurements where taken on two different days to check the reproducibility.

It is observed that the broadest supercontinuum is obtained for zero prechirp. It is also observed that if the prechirp is kept within ±1000 fs^2, corresponding to a variation of ± 5 cm in the SSMF length, the short wavelength supercontinuum edge will only vary a few nm. Finally, there is good agreement between the measurements taken on two different days, which points to that our setup is stable. The dependence of the short wavelength edge of the prechirp is much smaller than what was found in [2]. This might be due to the more distorted pump pulse quality used in this study

4.2 Dispersion of the HNLF

Various HNLFs with different dispersion characteristics were fabricated as described in section 2.1 to examine the influence of the dispersion of the HNLF on the supercontinuum performance. The characteristics of the fibers are summarized in Table 1. To obtain the 0.05 dB splice loss between HNLF and SSMF stated in Table 1 a special splicing technique is required. For convenience, a standard fusion splicer was used in this study, as the aim is a comparative study of different HNLF. So in this study, the splice loss between SSMF and HNLF is 1 dB.

First three different HNLF with dispersion characteristics as shown in Figure 5 left were examined. The dispersion and dispersion slope at 1550 nm of the three fibers are: HNLF A: -0.5 ps/(nm·km), 0.019 ps/(nm^2·km), HNLF B: 2.5 ps/(nm·km), 0.017 ps/(nm^2·km), and HNLF C: 8.7 ps/(nm·km), 0.029 ps/(nm^2·km). The zero dispersion wavelengths are HNLF A: 1588 nm, HNLF B: 1450 nm, and HNLF C: 1342 nm.



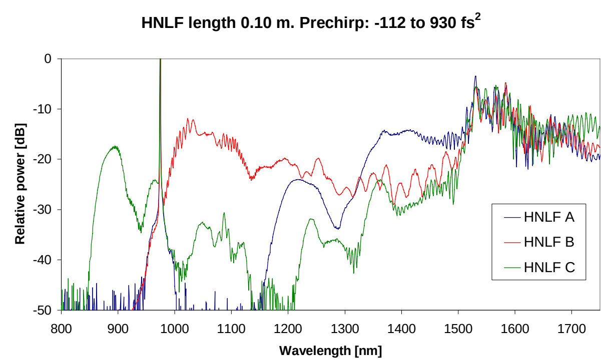


Figure 5. Left: Dispersion profile for three HNLF. Right: Measured supercontinuum spectra on 0.1 m of HNLF.

Figure 5 right shows measured supercontinuum spectra from 10 cm of HNLF. It is observed that a short zero dispersion wavelength provides the broadest supercontinuum This is in good agreement with the observations in [1]. HNLF C shows a short wavelength supercontinuum edge of 870 nm. To the best of our knowledge, this is record for a non-UV treated HNLF.

To examine the effect of dispersion slope three HNLFs with almost same zero dispersion wavelength and different dispersion slope have been compared. The measured dispersion for the three HNLFs are shown in Figure 6 left. The zero dispersion wavelengths are HNLF B: 1450 nm, HNLF E: 1428 nm, and HNLF F: 1440 nm. The dispersion and dispersion slope at 1550 m of the three fibers are: HNLF B: 2.5 ps/(nm·km), 0.017 ps/(nm^2·km), HNLF E: 3.5 ps/(nm·km), 0.024 ps/(nm^2·km), and HNLF F: 1.9 ps/(nm·km), 0.010 ps/(nm^2·km).

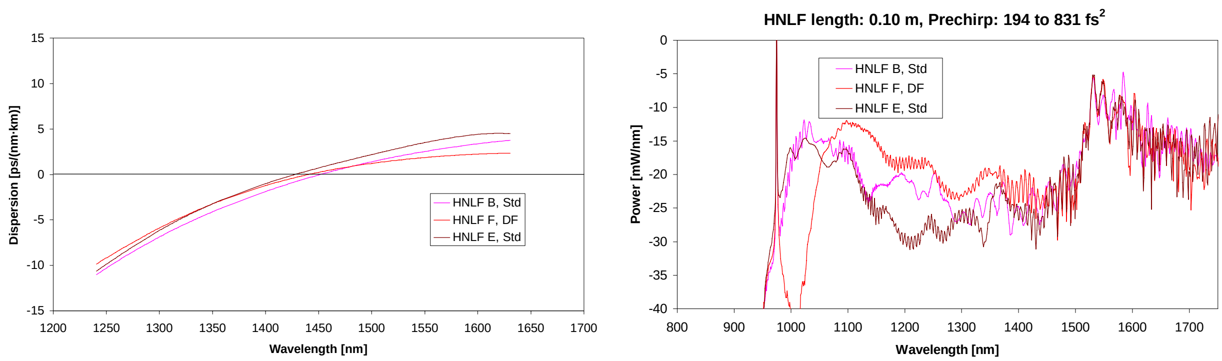


Figure 6. Left: Dispersion profile for three HNLF. Right: Measured supercontinuum spectra on 0.1 m of HNLF.

In Figure 6 right, the measured supercontinuum spectra are shown. The dispersion flattened HNLF F shows the narrowest supercontinuum.

4.3 Power level

To study the effect of power into HNLF on the supercontinuum a measurement series, where the pump power to the amplifier has been varied, was performed. For this study HNLF D was used. This fiber has a zero dispersion wavelength of 1396 nm, a dispersion coefficient at 1550 nm of 4.8 ps/(nm·km) and a dispersion slope at 1550 nm of 0.021 ps/(nm^2·km).

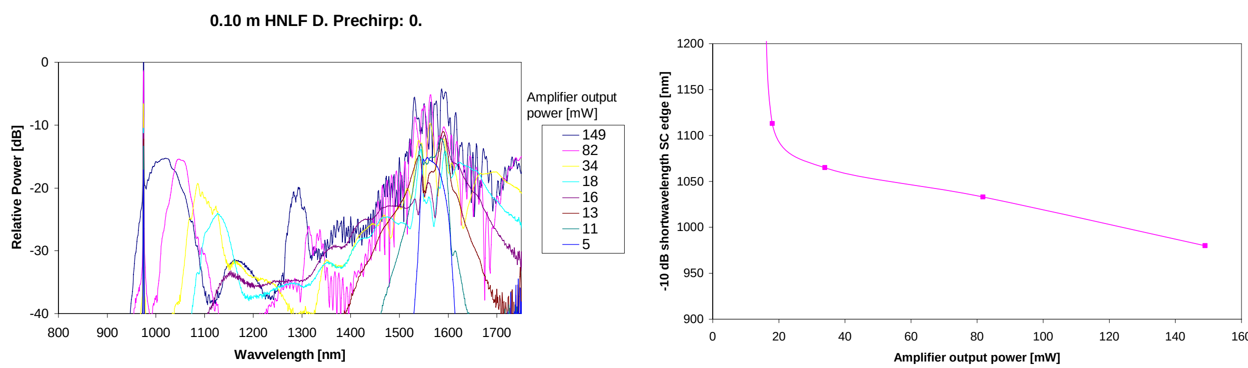


Figure 7. Effect power. Left measured supercontinuum spectra. Right: short wavelength supercontinuum edge as function of pump power.

Results on study of the effect of pump into the HNLF are shown in Figure 7. Measured spectra are shown in Figure 7 left. The short wavelength supercontinuum edge, defined as the shortest wavelength where the power is 10 dB lower than the peak power, as function of pump power is shown in Figure 7 right.

5. SUPERCONTINUUM RESULTS FOR PM-HNLF

For many applications it is important to have a supercontinuum with a known and stable state of polarization. This can be obtained with a PM-HNLF pumped with a PM femtosecond laser. Therefore supercontinuum generation in PM-HNLFs has been studied.

A true PM femtosecond laser was not available for this study. Instead the same setup as used for the non-PM HNLF was utilized. For the first study only a polarization controller was added on the SSMF between amplifier and HNLF. The polarization controller was adjusted for broadest supercontinuum generation. As with the non-PM HNLF a standard fusion splicer was used for splicing to the SSMF with a splice loss of 1 dB.

Four different PM-HNLF were manufactured with properties as shown in Table 2 and dispersion as shown in Figure 8, left.

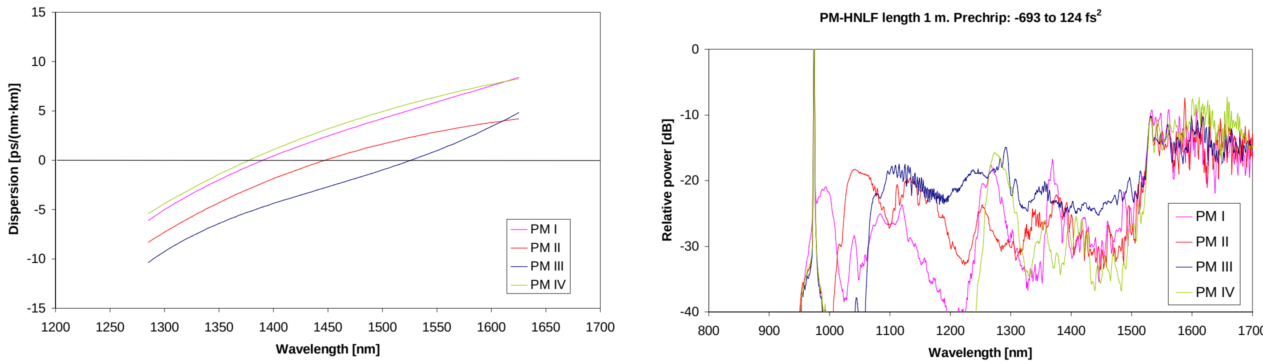


Figure 8. Left: Dispersion profile for four PM-HNLFs. Right: Measured supercontinuum spectra on 1 m of PM-HNLF.

The dispersion shown in Figure 8, left is measured using an unpolarized source. This gives a measure of the average dispersion of the two polarization axis, but the measurement is much more noisy compared to measurements on non-PM fibers. E.g. the dispersion crossing at long wavelength for PM I and PM II is believed to be a measurement artifact.

In Figure 8, right, the measured supercontinuum spectra for the four PM-HNLF are shown. For PM I to III, the same trend as for the non-PM HNLF is seen. The supercontinuum gets broader for decreasing zero dispersion wavelength. However, when the zero dispersion wavelength is decreased further from PM III to PM IV a significant narrowing of the supercontinuum spectrum is observed. This points to that a optimum exist for the zero dispersion wavelength, which yields the broadest supercontinuum spectrum. PM-HNLF III seems to be close to this optimum yielding a short wavelength supercontinuum edge of 980 nm.

PM-HNLF III was studied in more details. The dispersion was measured with a polarized source and the dispersion coefficient for the two axis measured. The results are shown in Figure 9, left. There is a difference in the dispersion of the two axis of around 1 ps/(nm·km).

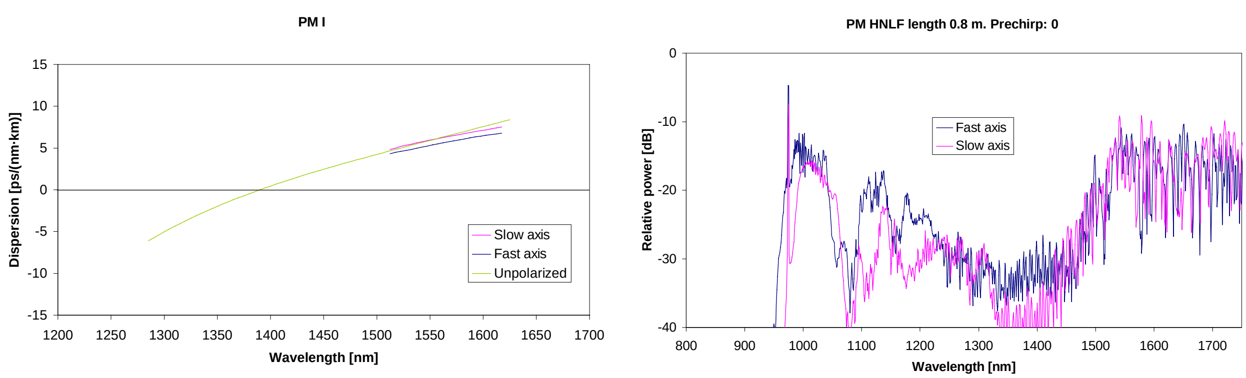


Figure 9. Left: Dispersion profile for PM-HNLF I. Right: Measured supercontinuum spectra on 0.8 m of PM-HNLF

To measure the difference in supercontinuum performance of the two axis a polarizer was inserted before the HNLF. Now the total loss between amplifier and HNLF increased to 2 dB. The polarization extinction ratio from the HNLF after splice to the polarizer was around 25 dB. The measured supercontinuum spectra are shown in Figure 9, right. The difference between the two axes is small despite the significant difference in dispersion. This is further evidence that the dispersion is close to optimum for broadest supercontinuum generation.

6. CONCLUSION

An experimental study of the effect of the dispersion on supercontinuum generation in highly nonlinear fibers (HNLF) has been performed. The best non PM HNLF showed a short wavelength supercontinuum edge of 870 nm, which is believed to be record for non UV treated HNLF. Supercontinuum generation in polarization maintaining HNLF has been demonstrated as well. The best PM-HNLF showed a short wavelength supercontinuum edge of 980 nm.

7. ACKNOWLEDGEMENTS

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