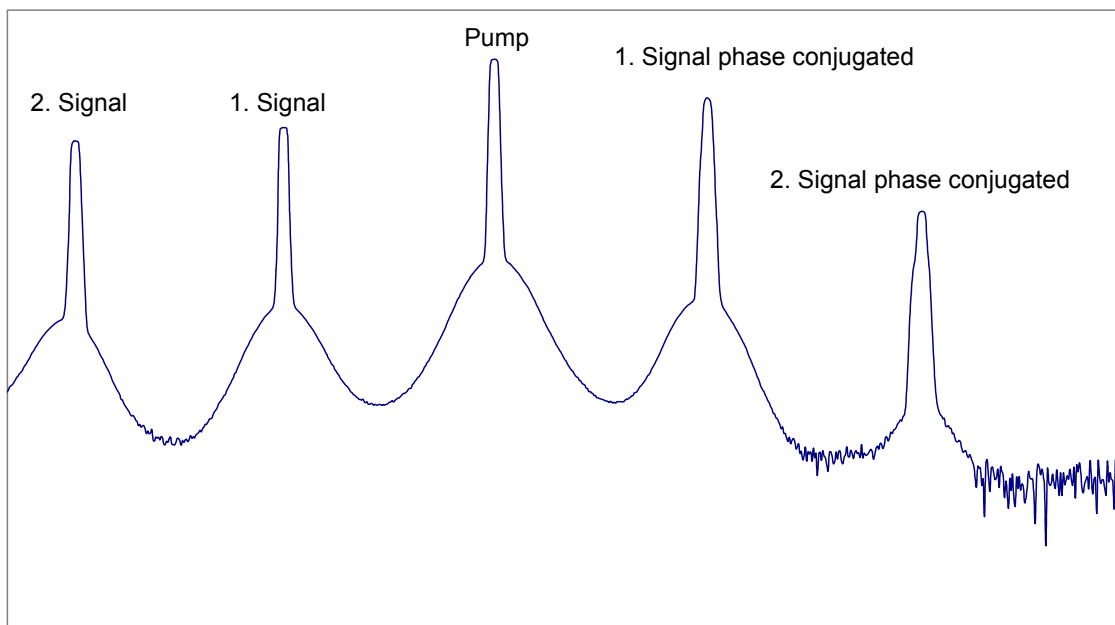


Highly Non-Linear Fiber



Applications, products and development targets

May 2004

Highly Non-Linear Fiber

Dispersion. Optical signals propagating in single mode optical fibers are influenced by group velocity dispersion. This arises from wavelength dependence of the glass refractive index (n) and a wavelength dependence on the wave number (k) through the mode effective index, resulting from the signal propagating in the fundamental mode. The two contributions are called material and waveguide dispersion, respectively. By designing the fiber geometry appropriately, the two dispersion contributions can cancel out (disregarding polarization effects), leaving a small residual dispersion over a large wavelength range. The OFS HNLF was designed to minimize the dispersion in the C-band wavelength range, however, the zero dispersion wavelength (ZDW) can be shifted to both the S- and L-band region. Figure 1 shows examples of measured dispersion curves for OFS HNLF.

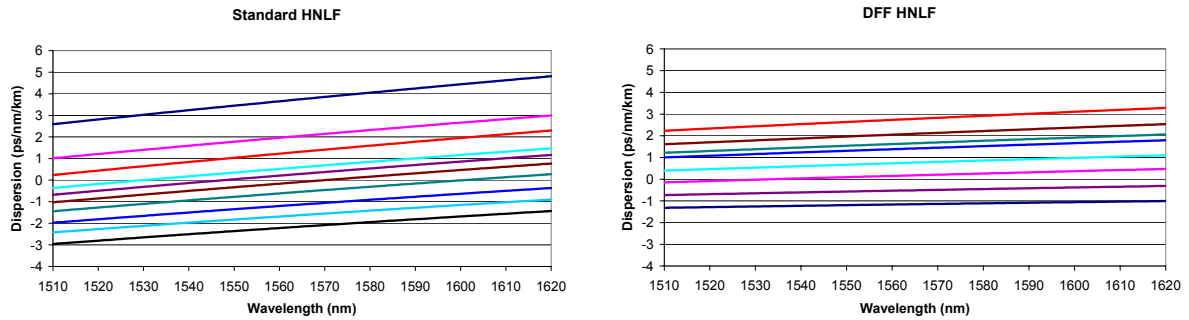


Figure 1. Examples of dispersion curves of the OFS HNLF. The data includes results for “standard” and “dispersion flattened” HNLF.

For a fiber with ZDW around 1550 nm, the dispersion slope of the standard OFS HNLF is approximately $0.02 \text{ ps/nm}^2/\text{km}$, hence, the dispersion between 1500 and 1600 nm is within $\pm 1 \text{ ps/nm/km}$ ⁽¹⁾.

Non-linearity. When the intensity of the optical signal increases, the interaction of the light and the matter becomes non-linear. For low signal intensities the induced polarization (\mathbf{P}) is proportional to the electric field (\mathbf{E}) of the applied optical signal. The linearity is expressed in the refractive index n . But for higher signal intensities the induced polarization is no longer directly proportional to the electric field, and a range of non-linear relations between electric field and induced polarization occur. Due to the symmetry of the glass on a molecular level, the main non-linear effects are third order, i.e., the non-linear part of the induced polarization is proportional to \mathbf{E}^3 . This has many consequences, but the most important is that the refractive index effectively becomes intensity dependent. This intensity dependence of the refractive index is expressed through the Kerr coefficient n_2 :

$$n = n_0 + I \times n_2 = n_0 + \frac{P}{A_{eff}} \times n_2 \quad (1)$$

n_0 is the linear refractive index and I is the intensity of the signal, which is related to the signal power (P) through the fiber effective area (A_{eff}). The fiber non-linearity is summarized in the non-linear coefficient:

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} \quad (2)$$

where λ is the signal wavelength. It follows directly, that γ increases directly with n_2 and inversely with A_{eff} . Because the OFS HNLF is designed for low dispersion in the C-band, the geometry of the fiber is essentially fixed, which in turn fixes the effective area. Consequently, n_2 must increase to increase γ . This

⁽¹⁾ The dispersion slope is not constant in this wavelength range, so the dispersion variation is slightly different.

can be done by higher Ge doping of the core. Unfortunately, this also increases the fiber loss and the variation of n_2 for practical core indices is less than a factor of two for silica fibers. As increased fiber loss decreases the fiber non-linear efficiency, as expressed by the effective length:

$$z_{eff} = \frac{1}{\alpha}(1 - e^{-\alpha L})$$

there is a trade off effective area and loss. The optimum depends on the length of the fiber required for a certain application as the effective length converges to the physical length for short fibers. The trade off between non-linearity, loss, and, dispersion, has led to a design with a typical non-linear coefficient of 10 - 11 $W^{-1} km^{-1}$, a Kerr coefficient of 3.0 - 3.25 $\times 10^{-20} m^2/W$ and an effective area of 11.5 μm^2 . Figure 2 shows measured non-linear coefficient for 20 samples of OFS HNLF whilst figure 3 shows the typical spectral loss for OFS HNLF.

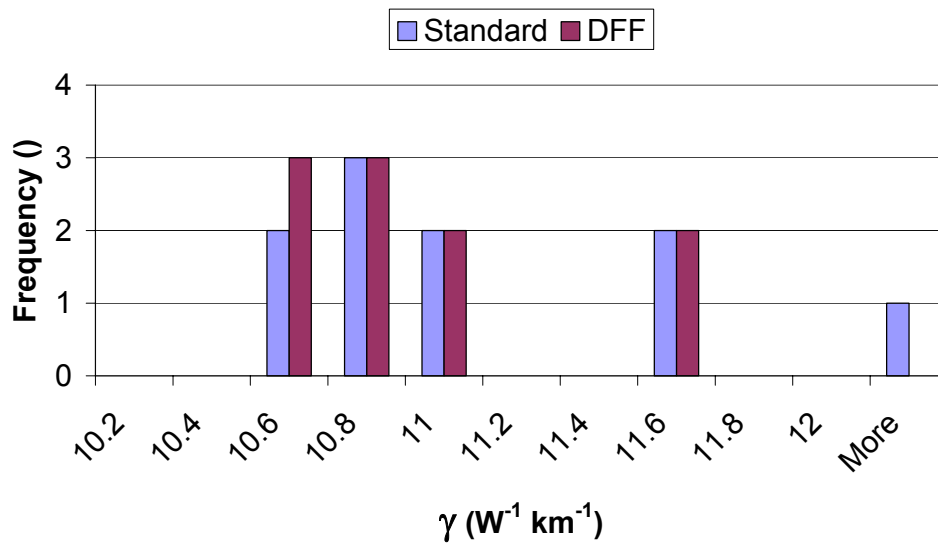


Figure 2. Fiber non-linearity of 20 HNLF samples⁽²⁾.

⁽²⁾ Measurement method: Boskovics et al, Optics Letters, Vol. 21., No. 24, December 1996, pp 1966-1968.

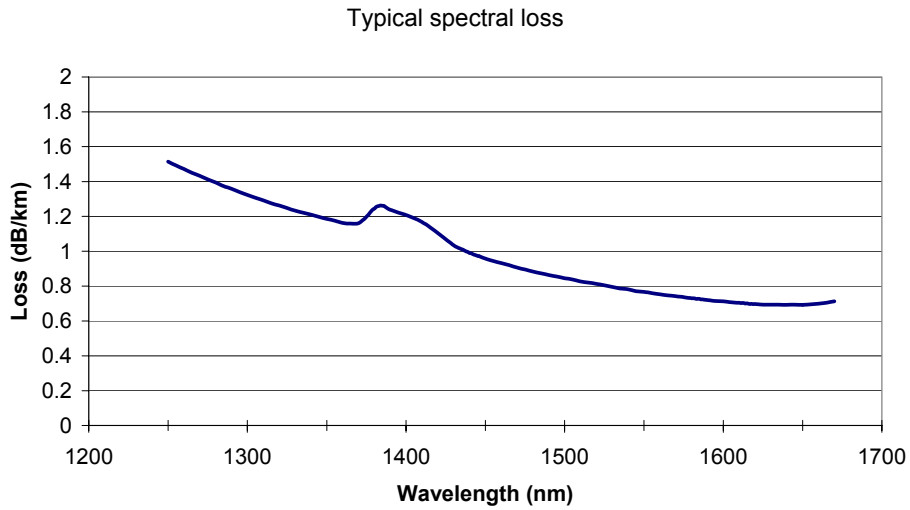


Figure 3. Typical spectral loss curve for OFS HNLf.

Splicing loss. Because of the small mode field diameter of the OFS HNLf compared to a standard single mode fiber (SSMF), a special splicing technique is required to obtain low splice loss directly between HNLf and SMFF. Figure 4 shows HNLf/SSMF splice losses for 21 modules (42 splices).

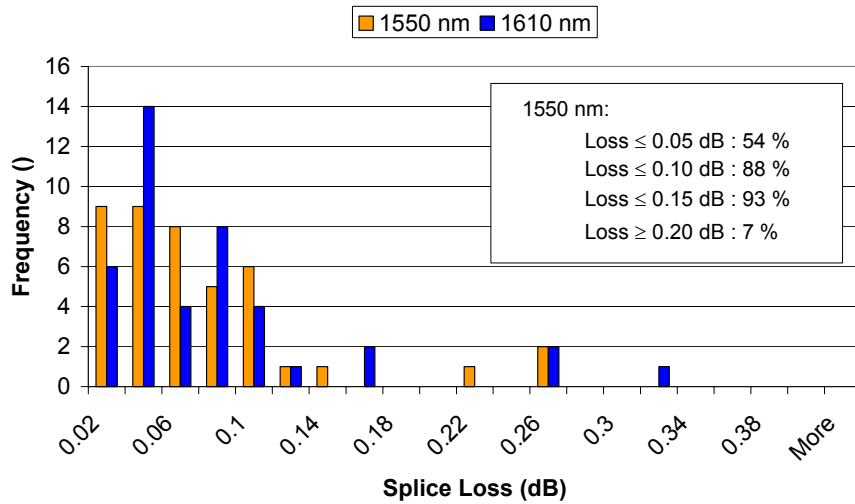


Figure 4. Splice loss of 21 HNLf modules with 42 HNLf/SSMF splices.

It is seen that the median splice loss is approximately 0.05 dB at 1550 nm and 1610 nm.



Leading Optical Innovations

PM-HNLF. Lately, there has been an increasing interest in broadband signal generation using HNLF, e.g., in ring configurations. There it can be advantageous to use a polarization maintaining HNLF. OFS is developing an elliptical core PM-HNLF with 80 μm cladding and 145 μm coating diameter. Because many applications of PM-HNLF requires short lengths of fiber, a small size spool is desirable. The OFS PM-HNLF is made with the small coating diameter of 80 μm to reduce the fiber PMD incurred by a small diameter coil. The design target is summarized below:

- Cut-off wavelength ≤ 1500 nm
- Mode-field diameter ≤ 4.5 μm
- Dispersion 2 ± 2 ps/nm/km
- Non-linear coefficient² ≥ 8 $\text{W}^{-1} \text{km}^{-1}$
- Birefringence $\geq 1.4 \cdot 10^{-4}$
- h-parameter $\leq 3 \cdot 10^{-4} \text{m}^{-1}$

Applications. The OFS HNLF has many applications, as it combines high non-linearity with a numerically small dispersion, and it has been used in experiments covering a wide range of applications:

- Pulse compression
- Optical regeneration
- Super continuum generation
- Parametric amplification
- Optical sampling
- Non-linear optical loop mirror optical time domain de-multiplexing
- Wavelength conversion



Leading Optical Innovations

Recent papers using OFS HNLF.

1. S. Radic, C. McKinstrie, R. Jopson, J. Centanni, A. Chraplavy, C. Jorgensen, K. Brar, C. Headley:
"Unimpaired Idler Generation in Four-Band Amplifiers Using Co- and Counterphased Modulation technique".
Technical Digest of OFC'03, paper ThK1, pp506-507.
2. J.W. Nicholson, A.K. Abeeluck, C. Headley, M.F. Yan, C.G. Jørgensen:
"Pulsed and CW Supercontinuum Generation in Highly Nonlinear, Dispersion Shifted Fibers",
To appear in Applied Physics B, 2003
3. Quang Le N.T., Carsten Gudmann Jørgensen, Lars Grüner-Nielsen and Bera Palsdottir:
"Enhancement of Non-Linear Response of a Highly Non-Linear Fibre Due to Raman Amplification".
Proceedings of ECOC'02; paper 3.2.5.
4. G. Raybon, Y. Su, J. Leuthold, R. Essiambre, T. Her, Carsten Gudmann Jørgensen, P. Steinvurzel, K. Dreyer, and, K. Feder:
"40 Gbit/s Pseudo-linear Transmission Over One Million Kilometers".
Technical Digest of OFC'2002, Postdeadline paper FD10.
5. S. Radic, C.J. McKinstrie, A.R. Chraplavy, G. Raybon, Carsten Gudmann Jørgensen, K. Brar, and, C. Headley:
"New Class of Continuous Wave Parametric Amplifiers".
Technical Digest of OFC'2002, Postdeadline paper FB5.
6. J. Li, J. Hansryd, P. O. Hedekvist, P. A. Andrekson and Stig Nissen Knudsen:
"300-Gb/s Eye-Diagram Measurement by Optical Sampling Using Fiber-Based Parametric Amplification".
OFC'2001, Postdeadline paper PD31, pp. PD31-1 - PD31-3.
7. Jianjun Yu, Palle Jeppesen and Stig Nissen Knudsen:
"80Gbit/s Pulsewidth-Maintained Wavelength Conversion Based on HNL DSF-NOLM Including Transmission Over 80 km of Conventional SMF".
Electronics Letters, Vol. 37, No. 9, pp. 577-579; 2001.
8. B.R. Washburn, J.W. Nicholson, S.A. Diddams, M.F. Yan, C.G. Jørgensen, N.R. Newbury:
"A Phase Locked Frequency Comb From an All-Fibre Supercontinuum Source".
ECOC'2003, Postdeadline paper Th. 4.1.3.
9. P. Westbrook, J. Nicholson, K. Feder, A. Yablon:
"UV processing of highly nonlinear fibers for enhanced supercontinuum generation".
OFC'2004, Postdeadline paper PDP27.