Dispersion measurement of large mode area Yb-doped double-clad fiber

Guo Liang, Wang Zefeng, Jin Aijun, Hou Jing, Chen Jinbao

(College of Optoelectronic Science and Engineering, National University of Defense Technology, Changsha 410073, China)

Abstract: Dispersion properties play a key role in high power supercontinuum generation in large mode area Yb-doped double-clad fiber. In this paper, an improved ultra-broadband and high resolution dispersion measurement system, based on a Mach-Zehnder interferometer and supercontinuum, was set up. The test arm of the interferometer was inserted with the fiber under test, and the reference arm of adjustable optical path length was tuned by a computer-controlled stepper motor with high resolution. The accurate dispersion characteristics of large mode area Yb-doped double-clad fiber was measured with a very short length of 27.2 cm. A series of interferometric fringes of different wavelengths, over a wide spectral range from 700 nm to 1 600 nm, were recorded to calculate the dispersion curve. Numerical calculation of the dispersion by finite element method was also made. The test results are in great agreement with numerical calculation, which shows good performance of the method and experimental system.

Key words: dispersion measurement; large mode area; Mach-Zehnder interferometer; supercontinuum

CLC number: O436 Document code: A Article ID: 1007-2276(2014)08-2673-05

大模场面积掺镱双包层光纤的色散测量

郭 良，王泽锋，靳爱军，侯 静，陈金宝

(国防科学技术大学 光电科学与工程学院，湖南 长沙 410073)

摘 要：大模场面积掺镱双包层光纤的色散特性在高功率超连续谱的产生中具有重要影响。搭建了一套基于马赫-曾德尔干涉仪和超连续谱光源的超宽波段、高精度的色散测量系统。干涉仪的测量臂插入待测光纤，参考臂通过高精度步进电机调节光程。通过此系统，仅使用 27.2 cm 长的样品对大模场面积掺镱双包层光纤的色散特性进行了精确测量。实验记录了 700~1 600 nm 范围内不同波长的干涉条纹，计算得到光纤的色散曲线。使用全矢量有限元法对光纤的色散进行了数值模拟，模拟结果与实验结果一致，证明了实验方法与系统的精确性。

关键词：色散测量； 大模场面积； 马赫-曾德尔干涉仪； 超连续谱

收稿日期：2013-12-10； **修订日期**：2014-01-25

基金项目：国家自然科学基金(11004247，11274385，61077076)

作者简介：郭良(1988-)，男，硕士生，主要从事光纤激光及光子晶体光纤方面的研究。Email:guoliang88123@163.com

导师简介：陈金宝(1970-)，男，研究员，博士生导师，博士，主要从事高能激光技术等方面的研究。

0 Inroduction

Yb-doped fiber is regarded as one of the most attractive active medium for fiber lasers and amplifiers due to its broad gain bandwidth, high output power, and excellent power conversion efficiency[1]. However, the scalability of output power of Yb-doped fiber lasers and amplifiers are limited mainly by amplified stimulated emission (ASE), nonlinear effects such as stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS), and fiber damage. All these limitations can be overcome with low numerical aperture (NA) large-mode-area (LMA) double-clad fiber, in which the amount of fluorescence captured by the core is limited and the thresholds of nonlinear effects and damage are increased[2]. Therefore LMA Yb-doped double-clad fibers are widely used in high power case[3-5].

Dispersion is one of the most significant parameters of fibers. The dispersion properties of LMA Yb-doped double-clad fibers will affect the output characteristics of lasers and amplifiers[6-7]. Recently, supercontinuum (SC) generation in nonlinear fiber amplifier based on LMA Yb-doped double-clad fiber are reported[8]. As we know, supercontinuum generation involves the interplay between nonlinear effects and dispersion. So it is of great significance to obtain the detail and accurate dispersion characteristics of the LMA Yb-doped double-clad fiber.

The time-of-flight method, phase shift method and interferometric method are the three widely used conventional dispersion measurement methods[9]. The time-of-flight method measures relative temporal delays for pulses at different wavelengths and is particularly useful to determine the ZDW. But it requires fast pulse detection and its resolution is restricted to ~50 ps by the temporal resolution of the detector. The phase shift technique measures the phase delay of a modulated signal as a function of wavelength, which demands a high optical signal-to-noise ratio to make precise measurements of phase. So the experimental setup is complicated and expensive equipments such as a high-speed optical modulator and an optical tunable filter are required. Its resolution is approximately 20 ps. Both the time-of-flight and phase shift techniques were developed for long optical fiber samples[10]. Interferometric technique could measure the delay spectra with a time resolution of ~0.1 ps which is more than two orders of magnitudes smaller than that of time-of-flight method. And moreover, it is sufficient to characterize fibers shorter than 1 m[9,11-12].

In this paper, we present an appropriate method to measure the accurate dispersion of the LMA Yb-doped double-clad fiber using a white light interferometer with supercontinuum as the light source. The zero dispersion wavelength (ZDW) of the fiber is 1.28 μm, and the dispersion curve is in great agreement with numerical calculation.

1 Expreimental method and setup

As the LMA Yb-doped double-clad fiber is costly and has a strong absorption around 1 μm, we should experiment with a short piece of fiber while ensuring a high measurement accuracy at a low cost. Based on above analyses, we adopt the interferometric method by the use of an ultra-broadband and high precision dispersion measurement system to test the dispersion characteristics of LMA Yb-doped double-clad fiber. This method utilizes a white-light interferometer employing a broadband supercontinuum source. The schematic experimental setup is depicted in Fig.1.

In our experimental setup, pulses centered at 1 064 nm with duration less than 1 ns emitted from the microchip laser are coupled into a 15 m long photonic crystal fiber (air hole diameter **d**=2.205 μm, pitch Λ=3.359 μm) by a microscope objective. Due to the interplay of dispersive and various nonlinear effects, the spectrum of the pulses is extended into broad-band supercontinuum from 470 to 1 700 nm at the end

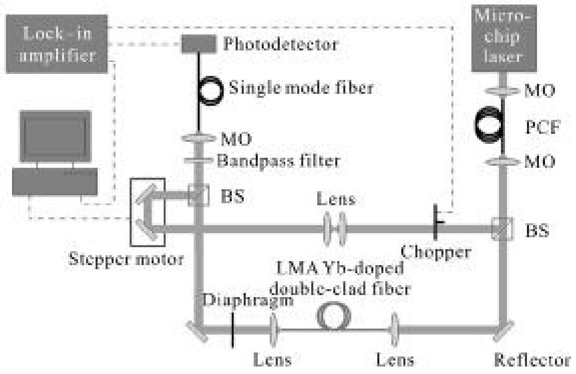


Fig.1 Experimental setup based on Mach-Zehnder interferometer with supercontinuum as light source

of the PCF. Since this supercontinuum has higher power and coherence than the conventional white-light sources such as incandescent lamp and LEDs, it is helpful in increasing the precision and accuracy of the measurement.

The generated supercontinuum pulses are collimated by a microscope objective and then enter a Mach-Zehnder interferometer. The beam gets devided by a beam splitter. One beam is coupled into the LMA Yb-doped double-clad fiber in the test arm. Since the size of the fiber is large and the NA is small, the coupling efficiency is low when using microscope objective. Thus we select a set of lenses (effective focal length **EFL**=8.00 mm, outer diameter **OD**=9.94 mm) to improve the coupling efficiency. Even so, a portion of optical energy is coupled into the inner cladding. A diaphragm is used to filter out the light propagated in the inner cladding in order to obviate its influence on the measurement. The other beam is injected into the reference arm. The two lenses in the reference arm are the same with those in the test arm, which make the dispersion induced by the two arms of the interferometer in balance. A computer-controlled stepper motor connected with two reflectors is used for adjusting the optical path of the reference arm. The resolution of the stepper motor is shorter than 8.5 nm, which ensures the measurement is precise. The two beams converge at the second beam splitter, pass through a narrow band-pass filter and then enter into a high sensitivity detector through a single mode fiber. The interference signal is recorded by a lock-in amplifier.

The total intensity **I** of the interference fringe is given by[13]

$$\mathbf{I}=\mathbf{I}_t+\mathbf{I}_r+2\sqrt{\mathbf{I}_t\mathbf{I}_r}\cos[\mathbf{k}(l_t-l_r)] \tag{1}$$

where $\mathbf{I}_t$ and $\mathbf{I}_r$ are the intensities of the beams in the test and reference arm, respectively. l_t and l_r are the optical paths. Symbol **k** denotes the wave number $\mathbf{k}=2\pi/\lambda$.

As the stepper motor is running under the control of computer, the optical path difference between the two arms changes. The lock-in amplifier records the interferometric fringe. The position of the stepper motor where the interferometric fringe reaches its peak, indicates the equalization optical path lengths between the two arms of the interferometer. A series of positions **x** are recorded by replacing band-pass filters with different central wavelengths λ. The measured data are fitted to a polynomial function with the experiential format[14]

$$x(\lambda)=\mathbf{A}+\mathbf{B}\lambda^{-4}+\mathbf{C}\lambda^{-2}+\mathbf{D}\lambda^{2}+\mathbf{E}\lambda^{4} \tag{2}$$

And the group velocity dispersion can be expressed as[15-16]

$$\mathbf{D}=\frac{2}{\mathbf{cL}}\frac{dx}{d\lambda} \tag{3}$$

Consequently, the dispersion curve is obtained through the measured data and numerical interpolation.

2 Experimental result and analysis

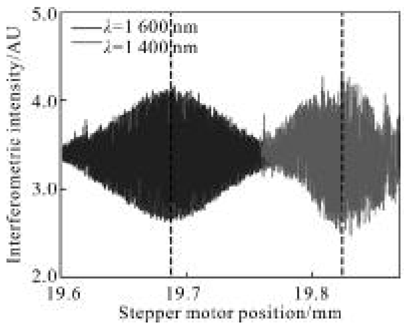
The fiber under test in our experiment is a piece of 27.2 cm long LMA Yb-doped double-clad fiber fabricated by Nufern Inc. The detail parameters including core diameter **d**, core numerical aperture $\mathbf{NA}_d$, inner-cladding diameter **D** and numerical aperture $\mathbf{NA}_D$, are listed in Tab.1.

When the stepper motor moves slowly and precisely, the interferometric intensity varies with the optical path difference of the two arms. The lock-in amplifier records this variation. So we obtain an interferometric

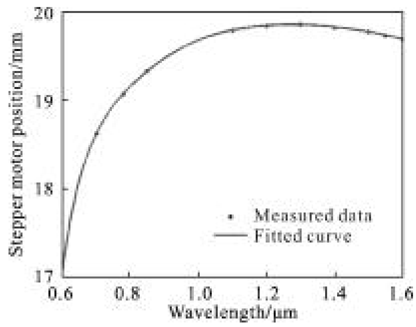
Tab.1 Parameters of measured LMA-Yb double-clad fiber

Type	d/μm	NA_d	D/μm	NA_D
LMA-YDF-25/400-VIII	25.0±2.5	0.060±0.010	400.0±15.0	⩾0.46

fringe, as shown in Fig.2(a). From the interferometric fringe we can calculate the accurate position where the fringe reaches its peak by mathematical method. Using bandpass filters with different central wavelengths, we have measured 10 such positions for different wavelengths from 700 to 1 600 nm. Fig.2(b) shows the measured data and the fitted curve.



(a) Interferometric fringe



(b) Stepper motor position

Fig.2 Interferometric fringes for central wavelengths at 1 400 nm (gray) and 1 600 nm (black); and positions of the stepper motor where the interferometric intensity is maximum

The group velocity dispersion curve is derived from the differentiation of the position curve. The result is presented in Fig.3. The zero dispersion wavelength of the LMA Yb-doped double-clad fiber can be found at 1.28 μm from the figure. We also made a numerical calculation of the dispersion curve (solid line in Fig.3) to be compared with the experimental result. The numerical calculation is done utilizing the material and structure parameters listed in Table 1 by finite element method. When we conduct the calculation, the numerical aperture NA of the core is used to compute the refractive index difference between the core and the inner silica cladding.

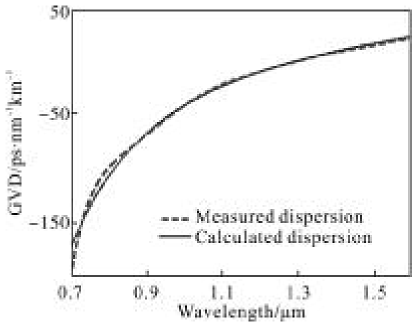


Fig.3 Measured and calculated dispersion curves

From Fig.3, we can find that the measured and calculated results are in great agreement, which proves the accuracy of our experiment method. Considering the high resolution of our equipments, the little difference between the two results should be mainly attributed to the inaccurate fiber parameters, which would greatly affect the propagating mode as well as the waveguide dispersion.

3 Conclusion

In conclusion, we presented a temporal interferometric technique for measuring the group velocity dispersion of a short-length of LMA Yb-doped double-clad fiber. This technique, which is appropriate for our test fiber in comparison with other methods and simple in data processing relative to the spectral interferometric technique[10,17], utilized a Mach-Zehnder interferometer with a broadband supercontinuum as light source. The dispersion curve is obtained accurately over a wide wavelength range from 700 to 1600 nm. We also calculated the dispersion numerically using the infinite element method and demonstrated good agreement between experiment and simulation. Our work should serve as a valuable guide for application of LMA Yb-doped double-clad fibers.

Reference:

[1] Paschotta R, Nilsson J, Tropper A C, et al. Ytterbium-doped fiber amplifiers [J]. IEEE Journal of Quantum Electronics, 1997, 33(7): 1049-1056.

[2] Tankala K, Carter A, Machewirth D, et al. PM double-clad fibers for high-power lasers and amplifiers [C], 2003: 220-229.

[3] Limpert J, Liem A, Schreiber T, et al. Power and energy scaling of fiber laser systems based on ytterbium-doped large-mode-area fibers[C]//Durvasula L N ed. Advances in Fiber Lasers, 2003: 135-147.

[4] Machewirth D, Khitrov V, Manyam U, et al. Large mode area double clad fibers for pulsed and CW lasers and amplifiers[C]//Durvasula L N ed. Fiber Lasers: Technology, Systems, and Applications, 2004: 140-150.

[5] Dong Z Y, Zou S Z, Han Z H, et al. High power, high energy nanosecond pulsed fiber amplifier with a 20-μm-core fiber[J]. Laser Physics, 2011, 21(3): 536-539.

[6] Kärtner F Xô, Keller U. Stabilization of solitonlike pulses with a slow saturable absorber [J]. Opt Lett, 1995. 20(1): 16-18.

[7] Renninger W H, Chong A, Wise F W. Pulse shaping and evolution in normal-dispersion mode-locked fiber lasers[J]. IEEE Journal of Selected Topics in Quantum Electronics, 2012, 18(1): 389-398.

[8] Song R, Hou J, Chen S, et al. High power supercontinuum generation in a nonlinear ytterbium-doped fiber amplifier[J]. Opt Lett, 2012, 37(9): 1529-1531.

[9] Cohen L. Comparison of single-mode fiber dispersion measurement techniques[J]. Journal of Lightwave Technology, 1985, 3(5): 958-966.

[10] Lee J Y, Kim D Y. Versatile chromatic dispersion measurement of a single mode fiber using spectral white light interferometry[J]. Optics Express, 2006, 14(24): 11608-11615.

[11] Gosteva A, Haiml M, Paschotta R, et al. Noise-related resolution limit of dispersion measurements with white-light interferometers[J]. J Opt Soc Am B, 2005, 22(9): 1868-1874.

[12] Diddams S, Diels J C. Dispersion measurements with white-light interferometry[J]. JOSA B, 1996, 13(6): 1120-1129.

[13] Wolf E, Born M. Principles of Optics [M]. New York: Pergamon Press, 1965.

[14] Liu X, Wang Z, Hou J, et al. Ultra-broadband dispersion measurement of photonic crystal fiber based on supercontinuum pulses [C]//Communications and Photonics Conference and Exhibition (ACP), 2009 Asia, 2009.

[15] Tateda M, Shibata N, Seikai S. Interferometric method for chromatic dispersion measurement in a single-mode optical fiber [J]. IEEE Journal of Quantum Electronics, 1981, 17(3): 404-407.

[16] Jin A, Wang Z, Hou J, et al. Experimental measurement and numerical calculation of dispersion of ZBLAN fiber [C]// 2011 IEEE International Conference on Electronics and Optoelectronics (ICEOE), 2011.

[17] Hoh D, Spittel R, Jamer M, et al. Chromatic dispersion measurement of microstructured optical fibers for nonlinear applications[C]//DGaO Proceedings, 2012.