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Polarization-maintaining higher-order mode fiber module with anomalous dispersion at 1 μm

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This Letter demonstrates a polarization-maintaining higher-order mode fiber module that has anomalous dispersion at 1 μm. The group velocity dispersion of the module is measured, showing a split of the two polarization axes. The excellent polarization-maintaining properties of the relevant fiber modes for the higher-order mode fiber are likewise demonstrated employing a new simple method for the measurement of the beat length of higher-order modes at a single wavelength. The higher-order fiber module is intended for group velocity dispersion compensation. © 2012 Optical Society of America

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Fiber lasers are of interest as they are user-friendly due to having no need for alignment as well as their compact size and stable operation. One challenge for short-pulse fiber lasers is to find a suitable fiber with anomalous dispersion at 1 μm. Higher-order mode (HOM) fibers have shown to have tailorable group velocity dispersion (GVD) and were exploited for GVD compensation first by using the HOM LP_{11} at 1550 nm [1]. However, exploiting a cylindrically symmetric mode allows for more stable operation [2]. The method is favorable for the GVD compensation since it has low loss, full-fiber integration, small effect of nonlinearities, and potentially third-order dispersion compensation [3]. A number of ultrashort pulse fiber lasers incorporating HOM fiber GVD compensation have been demonstrated [3–5], and the shortest pulse duration obtained is 57 fs with a repetition rate of 16.6 MHz [5].

Polarization-maintaining (PM) fiber has shown to increase the environmental stability of fiber lasers [6], and this Letter concerns the construction of a GVD compensating PM HOM fiber module.

A PM HOM fiber, a triple clad fiber or a so-called W-structure, which enhance the support of the LP_{02} mode, designed after the principle presented in [3] with the addition of two boron doped stress rods to supply birefringence needed to make the fiber PM, is used for GVD compensation. The HOM LP_{02} is shown to exhibit anomalous dispersion and may be used to compensate the normal dispersion of single-mode fiber (SMF) at 1 μm. The GVD compensating fiber module consists of the PM HOM fiber in which two long period gratings (LPGs), acting as mode converters (MCs), have been written. The basic scheme for GVD compensation is presented in Fig. 1.

The refractive index profile of a non-PM version of the HOM fiber is used in simulations performed with a scalar model. The simulations show that four modes are guided: LP_{01}, LP_{11}, LP_{02}, and LP_{21}. The simulations are used as reference for the measured data.

The GVD of LP_{01} and LP_{02} is measured with the phase delay method [7] (Dispersion/Strain 2800 from Photon Kinetics). The relative group delay is measured along both the fast and the slow axes.

First, the relative group delay measurement of the LP_{01} mode is presented. Only LP_{01} is launched into the fiber using a highly uniform fiber taper in the fiber under test (FUT) [8]. The relative group delay is measured in a fiber piece of close to 1 km of length. The setup includes a polarizer to launch into only one polarization axis at a time. The fiber taper does not reduce the polarization extinction ratio (PER) significantly, and the PER is measured to 25 dB. The multipath interference (MPI) is determined to be below −37 dB.

The measured relative group delay is presented in Fig. 2(a). The relative group delay is set to zero at 1015 nm. The group delay of the slow and the fast axes follow the same trend. Both curves show very good agreement with the simulated data for a non-PM HOM fiber. The measured curves are approximated with fourth-order polynomials; the polynomial fits are made to reduce numerical errors upon differentiation, and the chosen order of the polynomial reduces the impact of artifacts from this approximation. By differentiating the fourth-order polynomials, the GVD is extracted. The GVD as function of the wavelength is presented in Fig. 2(b) and shows good agreement with the simulated data. The insets in Figs. 2(a) and 2(b) show a split of the two polarization axes. The fundamental mode does thus exhibit a significant normal dispersion. A larger split of the polarization axes is seen towards the ends of the measurement interval. This originates primarily from the influence of the noise in the end points of the polynomial approximation. The uncertainty of the measurement procedure, increased by performing a differentiation to retrieve the GVD, as well as the simplicity of the scalar model, lead to the discrepancies between model and

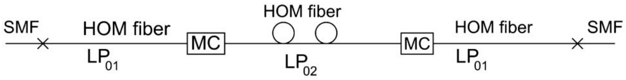

Fig. 1. Basic scheme for GVD compensation using a HOM fiber module. LP_{01} and LP_{02} describe the propagated fiber mode.

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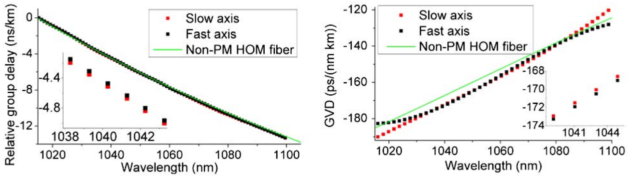

(a) (b)

Fig. 2. (Color online) (a) Relative group delay measurement of LP_{01} along slow and fast axis using the phase delay method. (b) GVD of LP_{01} based on numerical differentiation of the data in (a) along both fast and slow axes. The insets show zooms of the data.

measured data in Fig. 2(b). Including the polarizer in the setup contributes with a negligible error.

For the measurement of the relative group delay of LP_{02}, a GVD compensating module as depicted in Fig. 1, is employed. The FUT is close to 1 km. As for the fundamental mode, the relative group delay is measured along both polarization axes in the fiber. Writing LPGs in a PM HOM fiber entails that the conversion depth of the LPGs is not necessarily the same for both polarization axes. The two MCs tested have the largest conversion efficiency in the slow and fast axes, respectively. Thus for measuring the relative group delay of the slow axis, the source is launched into the slow axis and propagates in the slow axis until reaching the second MC, where the polarization is turned. For measuring the relative group delay in the fast axis, an opposite scheme is employed. Splice optimization for guidance of LP_{02} has been performed. The measured relative group delay is plotted in Fig. 3. The MPI of the module is found for both the slow- and fast-axis configuration to be better than −20 dB. The measured group delay within the bandwidth of operation for the GVD compensating HOM fiber module, plotted in Fig. 3, is approximated with fourth-order polynomials. Differentiating the polynomials render the GVD, which is plotted in the inset. The measured relative group delay of LP_{02}, plotted in Fig. 3, shows great similarity with the simulated data for the non-PM HOM fiber. A small split of the two polarization axes is observed.

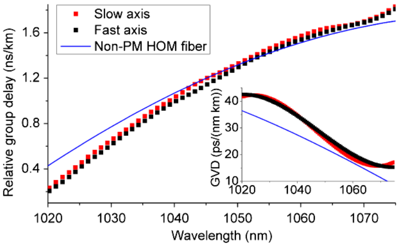

Fig. 3. (Color online) Relative group delay measurement for LP_{02} along slow and fast axes within the bandwidth of the GVD compensating HOM fiber module. In the inset, the GVD based on a numerical differentiation of the relative group delay is plotted.

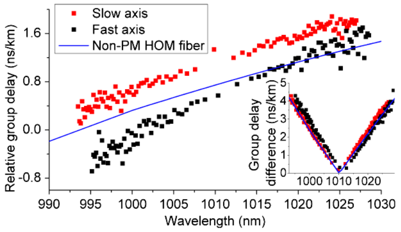

Fig. 4. (Color online) Indirect measurement of the relative group delay of LP_{02}. The measurement is based on the sum of the measurement of the absolute difference in the group delay of LP_{02} and LP_{01}, which is shown in the inset, and an extrapolation of the relative group delay of LP_{01}, plotted in Fig. 2(a).

The measured relative group delay of LP_{02} is subject to greater error compared to that of LP_{01}. This is the result of an increased amount of fiber not guiding the mode of interest as this measurement is carried out on a GVD compensating PM HOM fiber module. To expand the bandwidth for determination of the relative group delay of LP_{02}, an indirect method is used, exploiting an intermodal beating measurement and the measurement of the relative group delay of LP_{01}. With an intermodal beating measurement after the principle of [9], the absolute value of the group index difference of LP_{01} and LP_{02} is measured, so for the actual difference *a priori* knowledge from the simulations of the non-PM HOM fiber of the relationship between the group delay of LP_{01} and LP_{02} is applied. The absolute group index difference measured with an intermodal beating measurement is shown in the inset in Fig. 4. A sign change is applied to the absolute group delay difference for wavelengths shorter than the wavelength corresponding to zero difference in the group delay. Fourth-order polynomials, which are approximated to the measured relative group delay of LP_{01}, are extrapolated to cover the range of the intermodal beating measurement. Adding the relative group delay of LP_{01} renders the relative group delay of LP_{02}. This is plotted in Fig. 4 along with the simulated group delay of the non-PM HOM fiber. The indirect method shows the same trend as the directly measured relative group delay of LP_{02} but due to the contribution from the intermodal beating measurement the uncertainty becomes large towards the end points. There is a slight difference between the result from the direct and the indirect methods most likely originating from the intermodal beating measurement, which in the ends of the measurement interval has a larger degree of uncertainty. Note that measurement of the relative group delay of LP_{02} presented in Figs. 3 and 4 originates from different measurements and hence different offsets apply to the measurements.

The PM properties of the fiber may be characterized measuring the beat length given by: $L_B = \lambda / n_{\text{slow}} - n_{\text{fast}}$, where n_{slow} and n_{fast} are the effective refractive indices of the slow and the fast axes in the fiber [10].

Measurements of the beat length for few moded fibers may be performed applying the differential Rayleigh scattering, which requires cumbersome postprocessing but has a very broad spectral range for determining the beat length [11]. Here, a simple measurement scheme for determining the beat length of HOMs for a single wavelength is employed; this is a first to our knowledge. The measurement is carried out by expanding the procedure for SMFs presented in [10] to few moded fibers.

To launch only into the mode of interest, the beat length of LP_{01} is measured in a fiber including a fiber taper for stripping the HOMs [8] and the beat length of LP_{02} is measured on a GVD compensating PM HOM fiber module; the narrow-band source employed must thus be within the bandwidth of the module. The conversion depth of the MCs in the GVD compensating PM HOM fiber module is strongly dependent on the state of polarization (SOP) and the setup does thus in both cases include a polarizer upon launching into the FUT even though this is in general not required for this measurement procedure [10]. Ten beat lengths are measured to reduce the uncertainty.

For repetitive measurements, beat lengths of 2.7 mm (with no observable uncertainty) and 2.85 ± 0.19 are recorded for LP_{01} and LP_{02}, respectively. The source used is very narrow band (FWHM smaller than 0.1 nm at 1053 nm) and does not contribute with significant error. For measurement of 10 periods of the periodic change in the SOP, a measurement error of 1 mm may be achieved, thus approximately a 3% error, which is comparable to the uncertainty of the differential Rayleigh scattering method [11]. The results are compared to the beat length of a commercial PM SMF, which constitutes the remaining part of the module; see Fig. 1. The beat length of **ClearLiteTruePhaseFibers 980** is 3.0 mm at 1053 nm [12] and thus somewhat longer than the measured beat lengths, demonstrating excellent PM properties of the PM HOM fiber.

Characterization of the GVD compensating PM HOM module includes a MPI measurement, using an interferometric setup. From this measurement, the bandwidth of the module is determined. Also the PER of the assembled module is measured. The modules have an approximate length of 10 m. Modules with PER as good as 23.2 dB and MPI down to −39.7 dB can be realized. An MPI measurement is seen in Fig. 5; the module has an MPI of −39.7 dB at 1020 nm and a PER of 22.0 dB at 1030 nm. The 1 dB bandwidth is estimated to 41 nm; the MPI and bandwidth of the module are thus comparable to those achieved for non-PM GVD compensating HOM fiber modules [13]. The 3 dB bandwidth is estimated to 83 nm.

In summary, we have demonstrated a GVD compensating PM HOM fiber module with anomalous dispersion at 1 μm. The MPI is as low as −39.7 dB. The PM properties of the module are estimated determining the beat length to 2.7 and 2.85 mm for LP_{01} and LP_{02}, respectively. This renders the possibility of assembling a module with a PER of up to 23.2 dB. The 1 dB bandwidth of the module is determined to 41 nm.

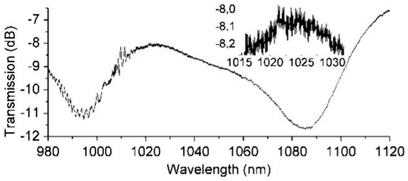

Fig. 5. MPI measurement of a GVD compensating PM HOM module with a resolution of 0.1 nm. The MPI and 1 dB bandwidth of the module are determined to −39.7 dB and 41 nm, respectively. The inset shows the basis of the MPI calculation.

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