All-Fiber Grating-Based Higher Order Mode Dispersion Compensator for Broad-Band Compensation and 1000-km Transmission at 40 Gb/s

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***Abstract*—We use a novel fiber-grating device to demonstrate the first polarization-insensitive all-fiber higher order mode dispersion compensator for broad-band dispersion compensation. Its low loss and high effective area have enabled transmission through 1000 km (10 $\times$ 100 km) of nonzero dispersion-shifted fiber (NZDSF) at 40 Gb/s.**

***Index Terms*—Gratings, optical fiber communication, optical fiber devices, optical fiber dispersion.**

I. Introduction

STRATEGIES for upgrading existing transmission links to achieve long-distance 40-Gb/s operation would require dispersion–compensation schemes that yield fully compensated transmission fiber links over the entire spectral range of interest. Broad-band compensation may be achieved by matching the relative dispersion slope values (RDS, defined as the ratio of dispersion slope to dispersion) of the transmission fiber and the dispersion compensating module (DCM). Nonzero dispersion-shifted fibers (NZDSF) exhibit high RDS ranging from 0.01/nm to 0.026/nm, and technologies that offer broad-band solutions include high RDS single-mode dispersion compensating fibers [1] (SM-DCF), Bragg-gratings [2], [3], virtually imaged phased-array devices [4], planar waveguide ring-resonators [5], and higher order mode DCMs (HOM-DCM) [6]–[8].

Of these, the broad-band solution that is deployed today is the SM-DCF, because it is inherently broad-band and low loss. The highest value of RDS reported [1] for SM-DCF is $\sim$0.0092/nm, which allows for adequate (92%) slope matching for truewave reduced slope fibers (TWRS). However, SM-DCF solutions for high RDS fibers result in propagation through small effective area fiber ($A_{\rm eff} \sim 15\ \mu$m^2), which can potentially cause nonlinear distortions in the signal.

HOM-DCMs utilize propagation in a higher order mode of a few-moded fiber to achieve large negative dispersion values and high RDS. There are several advantages to this approach: The higher order mode exhibits large negative dispersion, which decreases the length of fiber needed, thus lowering module loss. This mode also has a larger effective area, which increases the input-power threshold for nonlinear effects. Finally, a fiber can be designed to achieve very large RDS values, thus enabling slope matching to any NZDSF. The disadvantage is that the device requires discrete mode converters (MC) to access the higher order modes, which could increase the loss of the module. Poole *et al.* [8] showed error-free operation at 2.5 Gb/s using the LP_{11} mode as the higher order mode. However, the LP_{11} mode is inherently polarization sensitive, thus requiring polarization controllers in front of each module, not feasible in a real transmission link. Gnauck *et al.* [7] showed broad-band dispersion compensation using the LP_{02} mode at 40 Gb/s, but the loss of each module was 5.5 to 6 dB, and the module required polarization control at the input of the device.

In this letter, we demonstrate the first polarization insensitive, all-fiber HOM-DCM. The device has a bandwidth $>$40 nm and offers dispersion compensation over the entire C-band. In addition, the HOM-DCM has the lowest loss ($<$3.7 dB), polarization-mode dispersion (PMD $\sim$1 ps) and multipath interference (MPI $<-$42 dB) reported to date for this class of devices. This results in a high figure-of-merit for the module (FOM $=$ module dispersion/loss $=$ 177 ps/nm-dB). This is achieved due to the demonstration of a novel long-period fiber-grating device for broad-band mode conversion. Thus, every component in this device is fiber-based, enabling a low loss device.

40-Gb/s system tests on TWRS fiber show low power penalty achieved with this approach ($<$0.5 dB over 20 nm). The module matches or outperforms (in system penalty) the highest RDS SM-DCF that is commercially available because it yields a better RDS match with TWRS.

The HOM-fiber has large effective area (65 μm^2), which allows higher input powers into the module without incurring nonlinear distortions. The resultant higher OSNR has enabled transmission over a record length of 1000 km (10$\times$100 km) at 40 Gb/s without Raman amplification.

II. Device Characteristics

The schematic of the all-fiber HOM-DCM is shown in Fig. 1 and illustrates that the device consists of a 2-km spool of HOM fiber spliced on to two UV-induced long period gratings (LPG). The LPG convert the LP_{01} mode into LP_{02} and vice-versa at the input and output of the module, respectively. A key requirement for this device is that the mode conversion (MC) be strong ($>$99%) and broad-band ($\Delta\lambda$ should cover the C or L band).

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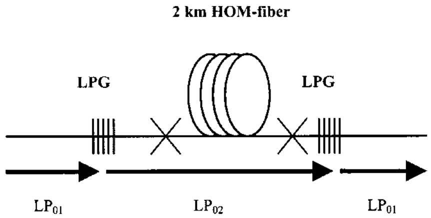

Fig. 1. HOM-DCM schematic. LPG = Long-period fiber grating. Block arrows represent propagation of dominant mode.

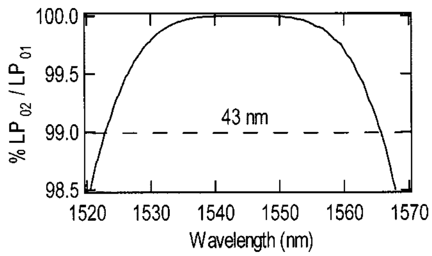

Fig. 2. UV-induced long-period grating spectra. More than 99% mode conversion over 43 nm. Covers entire C band.

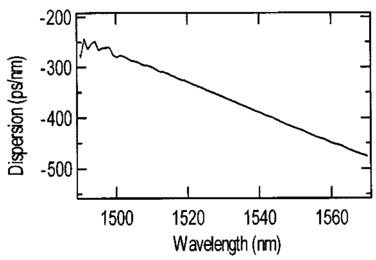

Fig. 3. Dispersion versus wavelength. $D(1550\ \text{nm}) = -420$ ps/nm·km; RDS = 0.008/nm smooth curve over entire C band. Ripples at $\lambda < 1510$ nm indicate MPI related degradations due to inadequate mode conversion.

The attractiveness of this solution is based on the fact that the LPG are written on the HOM-fiber itself. This reduces splice losses between the LPG-based mode converter and the 2-km spool of the HOM fiber. While LPG are commonly narrow-band devices (99% MC bandwidth <1 nm), these novel LPG offer >99% MC over 43 nm, covering the entire C-band, as shown in Fig. 2. This is inherent to LPG coupling characteristics when one of the modes is highly dispersive.

Dispersion measurements, made with a commercial test set, are plotted in Fig. 3. The HOM-DCM yields a dispersion of −420 ps/nm·km and an RDS ∼0.008/nm at 1550 nm. This corresponds to 100% compensation of a 100-km TWRS span at 1550 nm and would match 80% of the dispersion slope of the span. It must be emphasized that HOM fiber designs for achieving even higher RDS are feasible. Ripples in group delay for λ <1510 nm indicate the presence of intermodal interference and are consistent with the results of Fig. 2 that less than adequate (99%) MC occurs at these wavelengths.

The peak connector-to-connector loss of the HOM-DCM is only 3.7 dB, as shown in Fig. 4(a). This included ∼0.2 dB losses for the LPG-based mode converters, ∼0.6 dB loss for each splice between the HOM fiber and SMF pigtails, and a fiber loss of ∼1 dB/km. Also shown in Fig. 4(a) is the loss spectrum for SM-DCF with the highest RDS that is commercially available. The low-loss characteristic of this HOM-DCM is a

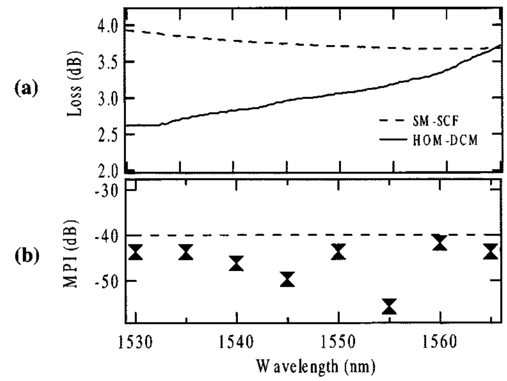

Fig. 4. (a) Loss spectra of HOM-DCM and SM-DCF. HOM-DCM losses <3.7 dB over C band. FOM ∼177 ps/dB-nm. (b) MPI <−42 dB over entire spectral range. Allows cascading more than 40 devices for <1 dB penalty.

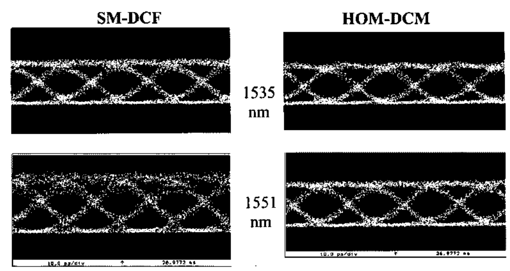

Fig. 5. 40 Gb/s NRZ eye diagrams. HOM-DCM open eye at both λ; SM-DCF degrades 15 nm away from optimal λ.

direct result of using in-fiber mode converters. The PMD of this module, measured using a commercial test-set yields an average DGD ∼1 ps. While a lower PMD value is desirable, the current value enables cascading several of these devices in a long-distance network.

A very important consideration with respect to HOM-DCM is that the HOM fiber is few-moded, making it susceptible to MPI. The measured values of MPI [Fig. 4(b)] assure that more than 40 such HOM-DCM may be cascaded in a span without effecting the bit-error-rate (BER) penalty by more than 1 dB [9].

III. Systems Demonstrations

The HOM-DCM is evaluated in a 100-km span of TWRS (span loss = 22.2 dB) with signals at a line rate of 40 Gb/s [return to -zero (RZ) as well as NRZ]. The performance is compared with a similar span that has a commercial high-slope SM-DCF. The commercial SM-DCF has an RDS of 0.0065/nm, while that for the HOM-DCM is 0.008/nm. The amount of negative dispersion in each module is adjusted to provide 100% compensation for the 100-km TWRS span at 1541 nm.

For a qualitative assessment, eye diagrams of a 40-Gb/s NRZ signal are measured at 1535 and 1551 nm (Fig. 5). The eye diagrams at the two wavelengths resemble each other for a link that is compensated with the HOM-DCM. On the other hand, in the case of the link compensated with SM-DCF, the eye diagram at 1551 nm appears to have deteriorated in comparison to that at 1535 nm. This is indicative of the fact that the HOM-DCM offers a better RDS match to the transmission fiber and thus fully compensates for dispersion over larger wavelength ranges.

The broad-band performance of the module is quantified by measuring BER power penalties in a 40-Gb/s RZ transmission

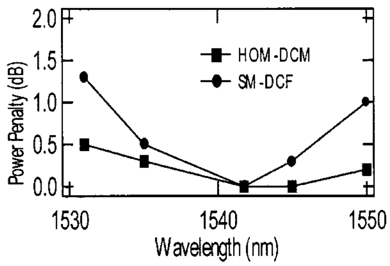

Fig. 6. Power penalty for 40-Gb/s RZ signals. Broad-band compensation with HOM-DCM: <0.5-dB penalty over 20 nm.

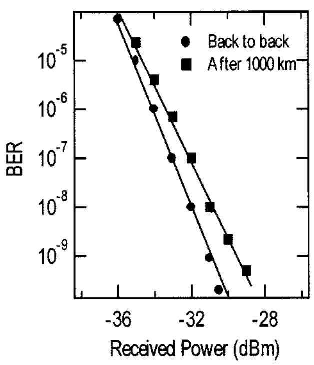

Fig. 7. BER after ten spans in a recirculating loop. 1000-km transmission distance achieved due to high-input power capability of HOM-DCM. Also confirms low MPI and PMD of the module.

system. The transmitted signals have a pulsewidth of ~8 ps. The back-to-back receiver sensitivity is -31 dBm, and the BER measurements are made on psuedorandom bit streams (PRBS) of $2^{31} - 1$ bits. Fig. 6 shows the BER power penalty at a BER of 10^{-9} compared to the back-to-back signal. The SM-DCF and HOM-DCM yield no penalty at 1541 nm, where both schemes completely compensate for dispersion. As is evident from Fig. 6, the rate of systems degradation away from the optimal wavelength is lower for the HOM-DCM. The SM-DCF bandwidth is 20 nm for less than a 1-dB penalty. In comparison, the HOM-DCM yields a penalty of only 0.5 dB in the same spectral range. This confirms the qualitative assertion based on the eye diagrams (Fig. 5), that the superior systems performance of this module is enabled by the high RDS of the HOM-DCM.

The HOM-DCM has an effective area >65 μm^2, which is at least four times larger than that of the high-slope SM-DCF. In addition, the length of fiber in the module is a factor of two lesser in the HOM-DCM. Thus, simulations indicate that up to 11-dB higher signal powers may be introduced into the HOM-DCM without incurring nonlinear distortions. This is experimentally confirmed by raising input power levels to as high as 10 dBm into the HOM-DCM while not detecting any nonlinearity related penalties.

It is expected that the high-input power capability would allow maintaining higher optical signal-to-noise ratio (OSNR) in the transmission span, and this in turn would extend the transmission distance of communication links. Long-distance transmission at 1550 nm is emulated by placing a 100-km span fully compensated with the HOM-DCM in a recirculating loop. The pulsewidths for these signals is ~2 ps. Fig. 7 shows BER curves after ten spans with 40-Gb/s RZ signals at 1550 nm. The systems penalty is only 1 dB after 1000 km of transmission at 40 Gb/s. Achieving this record distance of transmission required raising the input power into the HOM-DCM to 4 dBm. It is important to note that the 1000-km transmission distance was achieved without the aid of distributed Raman amplification in the span.

IV. Summary

We demonstrate the first polarization insensitive all-fiber HOM-DCM. The critical component is a novel broad-band in-fiber long-period grating. The module has the highest FOM and lowest MPI and PMD reported to date. Broad-band dispersion compensation has been demonstrated at 40 Gb/s, demonstrating that high RDS solutions may be obtained using the HOM-DCM. In addition, the high-input power capability of the module has enabled transmission over a record length of 1000 km of NZDSF with 100-km amplifier spacing at 40 Gb/s. Thus, the HOM-DCM may be a key enabler in long-distance high-bit-rate systems where high signal powers must be maintained to avoid OSNR degradations.

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