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Long-haul Dense Space Division Multiplexed Transmission over Low-crosstalk Heterogeneous 32-core Transmission Line Using Partial Recirculating Loop System

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***Abstract*—In this paper, we present long-haul 32-core dense space division multiplexed (DSDM) unidirectional transmission over a single-mode multicore transmission line. We developed a low-crosstalk heterogeneous 32-core fiber with a square lattice arrangement, and a novel partial recirculating loop system. The span crosstalk of the 51.4-km 32-core transmission line was less than −34.5 dB. This allowed the transmission of polarization division multiplexed 16 quadrature amplitude modulation (PDM-16QAM) signals through all 32-cores over a long distance exceeding a thousand km. We demonstrate 32-core DSDM 20 wavelength division multiplexed (WDM) PDM-16QAM transmission over 1644.8 km with a high aggregate spectral efficiency of 201.46 b/s/Hz. Additionally, we examine the effect of crosstalk on the transmission performance of each core, and show that the Q-penalty has strong correlation with inter-core crosstalk.**

***Index Terms*—Coherent communications, crosstalk, long-haul transmission, multicore fiber (MCF), optical communication systems, optical fiber communication, optical fibers, space division multiplexing (SDM), spectral efficiency, wavelength division multiplexing (WDM).**

I. INTRODUCTION

SPACE division multiplexing (SDM) has been studied intensively as the next generation multiplexing technology for increasing capacity of optical fiber transmission systems [1]. Many transmission experiments have been performed using multicore fibers (MCFs) or few-mode fibers (FMFs), and have demonstrated high capacity [2-6] and long-distance [7-14] transmission. Figure 1 shows the spatial multiplicity as a function of distance in recent SDM experiments. MCFs with seven to 19 cores, and FMFs with three to six modes were commonly used as the transmission media. With a view to further increase capacity, we have presented dense SDM (DSDM) transmission with over 30 spatial multiplicity by simultaneous use of multiple core and multiple mode multiplexing. Polarization division multiplexed 32 quadrature amplitude modulation (PDM-32QAM) signals were transmitted over 40.4 km 12-core × 3-mode multicore few-mode fiber (MC-FMF) with a high aggregate spectral efficiency (SE) of 247.9 b/s/Hz [15]. Subsequent experiments have further advanced multicore multimode transmission technology, including 200 Tb/s high capacity transmission over 7-core × 3-mode fiber [16], transmission of 12-core × 3-mode PDM-QPSK signals over 527-km realized by the first multicore multimode recirculating loop experiment [17], fabrication of 36-core × 3-mode fiber [18], demonstration of 19-core × 6-mode fiber and 2.05 Pb/s transmission capacity [19,20], and the realization of 19-core × 6-mode fiber with a relative core multiplicity factor of more than 60 [21]. Although these reports

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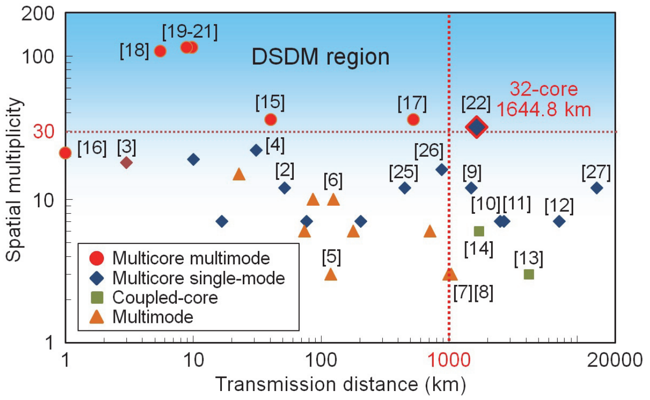

Fig. 1. Spatial multiplicity as a function of distance in recent SDM experiments

have shown the potential for further capacity scaling, the transmission distance was limited to around 500 km for the MC-FMFs with 36 spatial multiplicity [17], and less than 10-km for MC-FMFs with over 100 spatial multiplicity [18-21]. As regards long-haul transmission exceeding 1000 km, three-mode [7,8], 12-core bi-directional (six-core unidirectional) [9], seven-core [10-12], three- and six-coupled-core [13,14] transmission have been achieved. However, the spatial multiplicity of these experiments was less than seven. In future scalable and flexible optical transport network, long-haul DSDM system with more than 30 spatial channels and over 1000 km transmission distance is necessary for application to terrestrial networks. To reach this target with multicore transmission requires overcoming the tradeoff between increasing core-count, maintaining sufficient effective area (A_{eff}), and reducing inter-core crosstalk within the limited cladding diameter considering fiber reliability.

In this paper, we describe the first demonstration of the long-haul DSDM transmission with over 30 spatial multiplicity and over 1000 km distance [22]. First, we review our low-crosstalk heterogeneous 32-core single-mode transmission line and our novel partial recirculating loop system, and then we present the experimental demonstration of the 32-core single-mode unidirectional transmission of PDM-16QAM signals over 1644.8 km. In addition, we investigate the effect of inter-core crosstalk on transmission performance.

This paper is organized as follows. Section II presents the low-crosstalk DSDM transmission line consisting of a heterogeneous single-mode 32-core fiber and free-space optics type fan-in/fan-out (FI/FO) devices. Section III reviews the experimental setup of conventional long distance transmission experiments and proposes our novel partial recirculating loop system. Section IV describes the experimental setup and Section V discusses the experimental results of the long-haul DSDM transmission and the verification of the relation between inter-core crosstalk and transmission performance. Section VI summarizes the main content and concludes the paper.

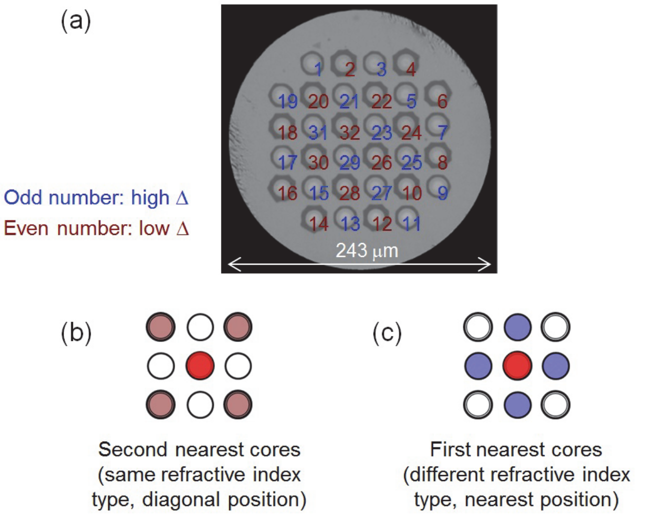

Fig. 2. (a) Cross sectional view of the heterogeneous 32-core single-mode MCF, (b) four cores in the diagonal position with the same refractive index type relative to the center core, and (c) four cores in the nearest position with the different refractive index type relative to the center core.

II. LOW-CROSSTALK 32-CORE TRANSMISSION LINE

We have previously designed and fabricated a heterogeneous 30-core single-mode MCF using four types of refractive index design, and a homogeneous 31-core quasi-single-mode MCF [23]. The core arrangement of both of these fibers were based on a hexagonal closed-pack structure, where the 30 and 31 cores were densely arranged within a cladding diameter of 228 and 231 μm, respectively, typical for an MCF. The fiber length was 9.6 and 11.0 km, and the A_{eff} at 1550 nm was 77 and 75 μm^2, respectively. The span crosstalk including fan-in/fan-out (FI/FO) devices of the 30-core and 31-core fiber was −31.9 and −21.6 dB, respectively. We define the inter-core crosstalk as the difference between the power of light output from the core under measurement when light was input only to the core under measurement and when light with equal intensities were input to all other cores. Although we showed that these DSDM fibers are capable of transmitting PDM- quadrature phase shift keying (QPSK) and PDM-16QAM signals, further reduction of inter-core crosstalk was required in order to realize long-haul DSDM transmission.

We have designed and fabricated a novel heterogeneous 32-core single-mode MCF to realize a low-crosstalk DSDM transmission line suitable for long-haul transmission. Figure 2 (a) shows the cross sectional view of the heterogeneous 32-core fiber [24]. A square lattice arrangement effectively minimizes inter-core crosstalk for heterogeneous MCF having two types of refractive index designs. The odd and even numbered cores representing cores with higher and lower refractive index difference, respectively, were placed adjacent to each other to suppress crosstalk. Trench structure was formed around each core for additional crosstalk reduction. The length of the fabricated MCF spool was 51.4 km, the core pitch was 29.0 μm, and the cladding diameter was 243 μm. The cutoff wavelength

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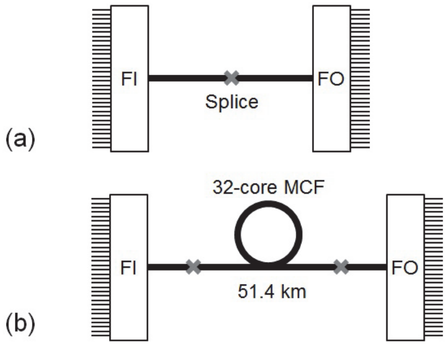

Fig. 3. Schematic diagram showing the components and splicing points for (a) measuring the characteristics of the free-space optics based 32-channel FI/FO devices, and (b) constructing the 32-core DSDM transmission line.

at a length of 1 km was < 1.53 µm. The attenuation and the A_{eff} at 1550 nm was 0.24 dB/km and > 80.3 µm^2, respectively.

The inter-core crosstalk of the MCF depended on the position of the cores. The worst crosstalk was < −39.4 dB when light was input to the second nearest cores (four adjacent cores with the same refractive index type in the diagonal position relative to the core under interest as shown in Fig. 2 (b)). On the other hand, the inter-core crosstalk was < −54.0 dB when light was input to the first nearest cores (four adjacent cores with the different refractive index type in the nearest position relative to the core under interest as shown in Fig. 2 (c)), and it was negligible even though the inter-core distance was smaller than that of the cores in the diagonal position. This result reveals that the inter-core crosstalk from cores with the different refractive index type is effectively suppressed by the destructive interference of light due to difference in propagation constants.

We used free-space optics based [25] 32-channel FI/FO devices for multi/demultiplexing light into/from the 32-core fiber. First, the MCF-side of the FI and FO devices were directly spliced as shown in Fig. 3(a), and the characteristics were measured. The insertion loss ranged from 0.8 to 1.4 dB, and the worst crosstalk ranged from −39.5 to −46.7 dB at 1550 nm. Then, the FI and FO devices were each spliced to the input and output of the 51.4-km spool of the 32-core MCF, respectively, to construct a 32-core DSDM transmission line. The total span loss and the worst inter-core crosstalk including the FI/FO devices were < 14.1 dB/ span and < −34.5 dB/span at 1550 nm, respectively.

Figure 4 shows the crosstalk after 1000-km transmission as a function of the number of core per fiber in a single-mode MCF. The filled plots show characteristics of an MCF transmission line including a fiber and FI/FO devices, and the blank plots show characteristics of a plain MCF. The 1000-km crosstalk was estimated from per span or per length crosstalk values given in references assuming that the crosstalk accumulates linearly with distance. The dotted lines also shown in the figure are the crosstalk levels required for various modulation formats assuming 0.5 dB penalty [26,27]. Crosstalk would normally increase when we increase the number of core in an MCF. Technique such as bi-directional transmission may reduce crosstalk. However, no MCF transmission lines have ever reached the target area of over 30 cores and a worst crosstalk of less than around −19 to −31 dB/1000 km. By the heterogeneous design and the square lattice arrangement, we have successfully reduced the worst crosstalk to < −21.6 dB even after 1000 km making long-haul DSDM transmission feasible for the first time.

III. Partial Recirculating Loop System

Features of long distance transmission experiments over an MCF transmission line are listed in Table 1. Various experimental setups have been employed for approximating long distance MCF transmission line. The commonly used

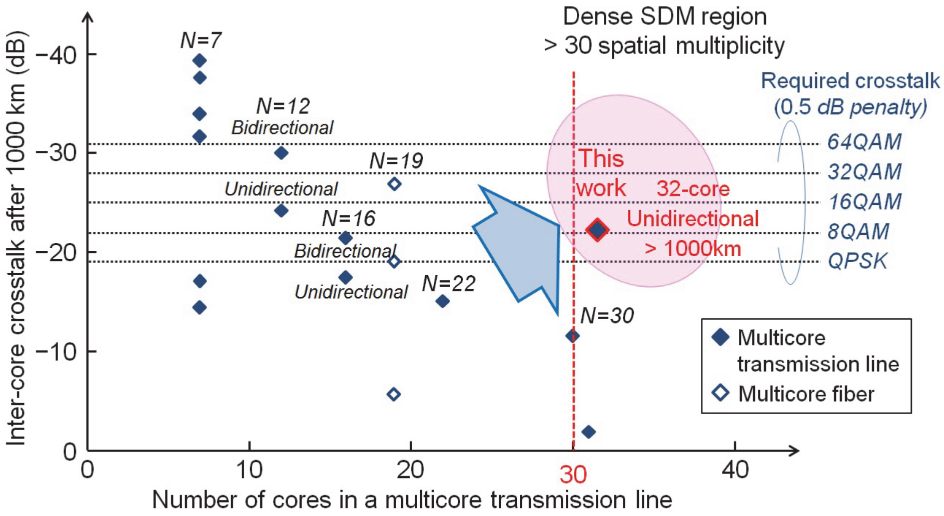

Fig. 4. Crosstalk after 1000-km transmission as a function of the number of core per fiber in a single-mode MCF. The filled and blank plot shows characteristics of multicore transmission line including FI/FO devices, and multicore fiber, respectively. Dotted lines show the crosstalk levels required for various modulation formats assuming 0.5 dB penalty.

method involves parallel recirculating loop system with core averaging by core-to-core rotation [9-12,28], without core averaging [17], and with mixing of signals between cores during propagation [13,14]. These experiments represent long-distance parallel transmission over each core in an MCF. On the other hand, the method requires *N* sets of optical components to construct parallel recirculating loops. To date, up to 12 parallel recirculating loops with 12-core MCFs have been demonstrated [9,28].

As an alternative to parallel core transmission, transmission experiments over serially connected cores of an MCF were reported [29,30]. In a bi-directional transmission experiment over a 16-core fiber, eight cores were connected in series to transmit in one direction and the remaining eight cores were connected in series to transmit in the opposite direction. This yielded a serially connected bi-directional 880-km (=55 km × 8 cores × 2 directions) transmission line [29]. In another experiment, 12 cores of a 12-core MCF were connected in series to construct a span of 552 km (=46 km × 12 cores), and a recirculating loop experiment was conducted with this serially-connected span [30]. The configurations of these experiments are simple and require few optical components. On the other hand, the drawback is that the measurement cannot distinguish the performance of individual cores.

The parallel recirculating loops with core averaging and the serially connected measurement may be a good method to approximate an MCF transmission line when the variation among core is modest, whereas the parallel recirculating loops without core averaging can measure the worst case performance, and is suitable for an MCF transmission line such as a high-core count MCF having variations in loss and crosstalk among cores depending on the core position. To characterize a long-haul MCF transmission line with good degree of approximation, it is favorable to have the ability of measuring performance of each core. However, an MCF having many cores, in particular, those with over several tens of cores, requires massive optical components to construct a full recirculating loop system.

We propose a novel partial recirculating loop system as shown in Figure 5 as an effective method for characterizing long distance transmission performance of an MCF for DSDM transmission. In this experimental setup, we form recirculating loops with part of the cores of an MCF including cores under measurement, and load non-recirculating signals to all other cores of an MCF. The optical power of signal input to each core of the MCF is set at the same value. In the initial experimental setup reported in [22], we constructed five recirculating loops, and configured the transmission line so that the recirculating signals are input to the core under measurement and the four adjacent cores with the same refractive index type in the diagonal position relative to the core under measurement as was shown in Fig. 2 (b) having higher inter-core crosstalk in the MCF. Non-recirculating signals are input to all other cores. With this setup, recirculating signals were loaded to cores that could have larger effect on the core under measurement during propagation in the MCF to approximate a full parallel recirculating loop system. We incorporated 32 channel matrix switches into the transmission line to cross-connect cores of the MCF with the recirculating loops and non-recirculating crosstalk signals, and switched the core connections for each measurement. Suppose that when core #28 was under measurement, cores #28, #12, #14, #26, and #30 were selected to form recirculating loops #1 to #5, respectively, while the remaining 27 cores were loaded with non-recirculating signals. The same operation is to be performed for characterizing other cores.

TABLE I
FEATURE OF LONG DISTANCE TRANSMISSION EXPERIMENTS OVER AN MCF TRANSMISSION LINE

Refs.	Number of cores	MCF structure	Span length (km)	Experimental setup	Inter-core crosstalk (dB)	Modulation format	Transmission distance (km)
[28]	12	Dual ring	50	12 parallel loops, 3-core rotation, bi-directional	−50 dB/span at C-band	PDM-32QAM	450
[9]						PDM-16QAM	1500
[10]	7	Hexagonal	40	7 parallel loops, 7-core rotation	−29.6 dB/span at MC-EDFA	PDM-QPSK	2520
[11]	7	Hexagonal	76.8	7 parallel loops, 7-core rotation	−34 dB/span	PDM-QPSK	2688
[12]	7	Hexagonal	45.5	7 parallel loops, 7-core rotation	−51 dB/span, pair of cores	PDM-QPSK	7326
[17]	12	Square lattice, heterogeneous	52.7	12 parallel multimode recirculating loops	−48.4 dB /500km	PDM-QPSK	527
[13]	3	3 coupled-core	60	3 parallel recirculating loops	-	PDM-QPSK	4200
[14]	6	6-coupled-core	31	6 parallel recirculating loops	-	PDM-QPSK	1705
[29]	16	Square lattice, heterogeneous	55	Serial connection of 16 cores, bi-directional	−34 dB/span	PDM-16QAM	880
[30]	12	N/A	46	Single recirculating loop with serial connection of 12 cores	−54 dB/span	8D-APSK	14350
[22]	32	Square lattice, heterogeneous	51.4	Partial recirculating loop system	−34.5 dB/span	PDM-16QAM	1644.8

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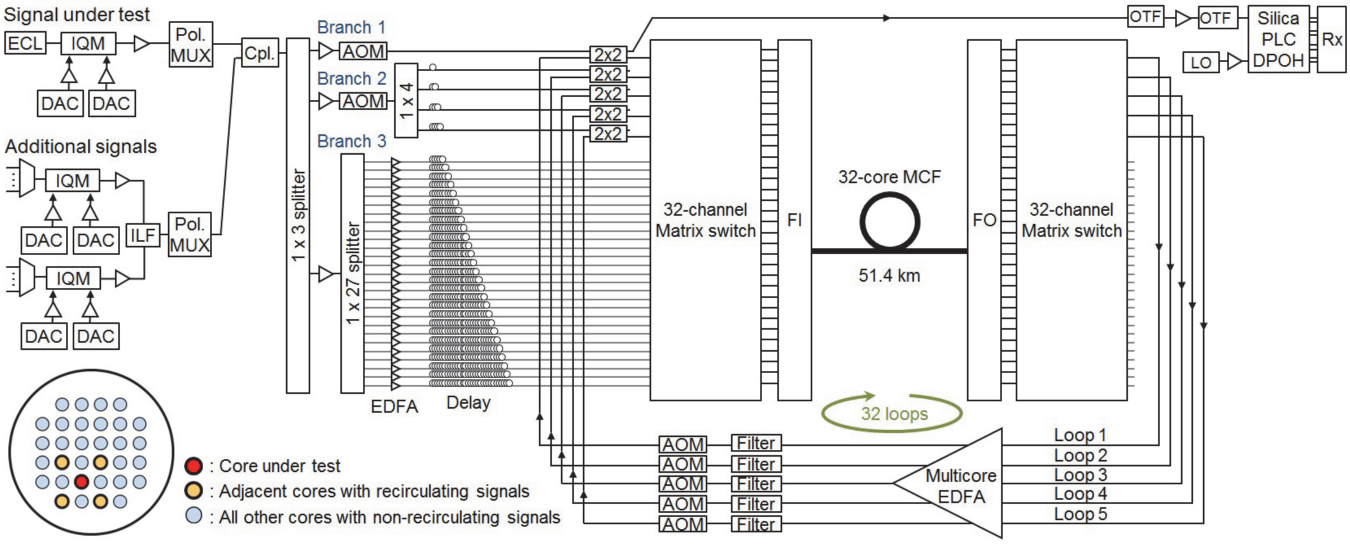

Fig. 5. Experimental setup with a novel partial recirculating loop system.

IV. Experimental Setup

We conducted transmission experiments using the low-crosstalk single-mode DSDM transmission line, and the partial recirculating loop system we described in the previous sections.

At the transmitter, the signal under test was generated using a tunable external-cavity laser (ECL) with ~60-kHz linewidth and was modulated by an IQ modulator (IQM). Additional 19 odd and even channels around 1549.1 to 1551.0 nm were generated using DFB lasers with 2-MHz linewidths and were wavelength multiplexed, separately modulated by IQMs, and combined by a 12.5/25 GHz interleave filter. All signals were digitally generated by the IQMs, each driven at 12 Gbaud and reshaped by a root-raised-cosine filter with 0.01 roll-off factor. Different pieces of pseudo-random-binary-sequence (PRBS) of length 2^{23-1} were used for each IQM to generate multi-level 16QAM signals. Signals with a frame length of 31250 symbols comprised a payload, 1.63 % overhead for training sequence, and 20 % overhead for forward error correction (FEC). The signal under test, and the remaining 19 wavelength channels were each polarization-division multiplexed by a PDM emulator with a 10 ns delay, and were combined with a 2 × 1 optical coupler. This yielded 12.5-GHz-spaced 20-DWDM 96-Gb/s PDM-16QAM signals.

The signal generated at the transmitter was split into three branches. The first branch was used for the core under measurement in loop #1, and the second branch was further split into four, which were used to provide recirculating crosstalk signals for loops #2 to #5. The third branch was further split into 27, and these signals were used as non-recirculating signals. The 32 signals were relatively delayed by 0, Δt, 2Δt, … , and 31Δt with a unit time delay Δt of 20 ns for decorrelation of signals between the 32 cores. The optical power of the DWDM signals input to the 32-core MCF was optimized at −10 dBm/wavelength/core.

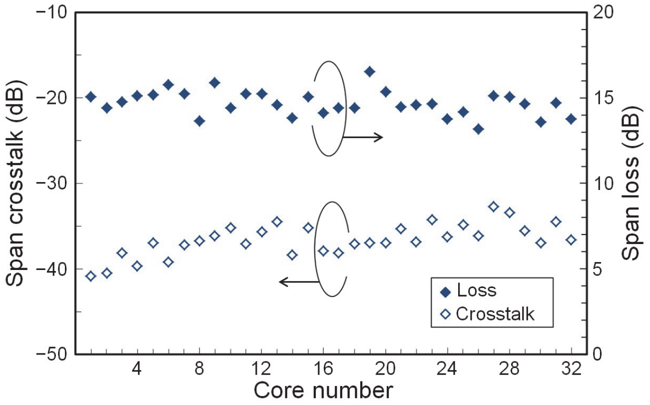

Fig. 6. Span crosstalk and loss of the DSDM transmission line measured at the center wavelength, including 51.4-km 32-core fiber, 32-channel FI/FO devices, and 32-channel matrix switches.

The partial recirculating loop system consisted of the first and second 32-channel matrix switches, a 51.4-km spool of the 32-core fiber, 32-channel FI/FO devices, and five parallel recirculating loops. Signals in the loops were amplified by five channels of a seven-core erbium-doped fiber amplifier (EDFA) [31]. The 32-channel matrix switches were used to select cores and cross-connect the paths of the input and output ports of the transmission line for each measurement as described above.

At the receiver, the signal from the core under test was filtered by a tunable optical filter and input to a planar lightwave circuit (PLC) type dual polarization optical hybrid (DPOH). It was then digitized at 40 GS/s using a four-channel digital storage oscilloscope and stored in sets of 4M samples. In the receiver-side offline processing, front-end error correction, chromatic dispersion compensation, and frequency-offset cancellation were first performed. Then, equalization was carried out using 64 T/2-spaced-taps LMS-based 2 × 2 frequency domain equalization (FDE) combined with phase

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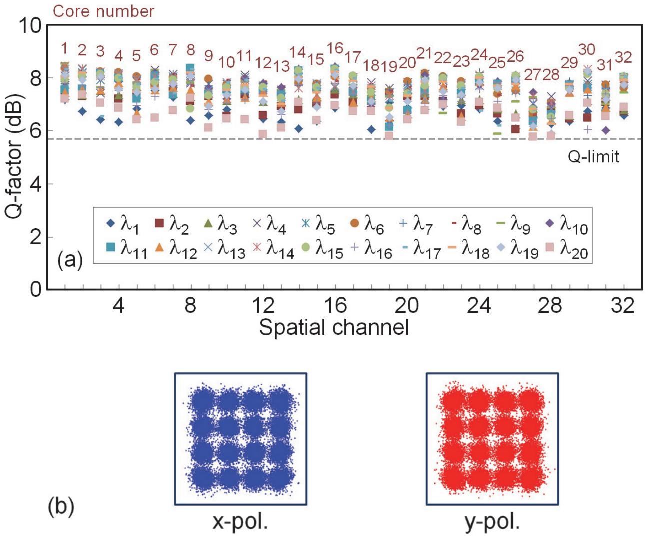

Fig. 7. Measured (a) Q-factors for 20 DWDM × 32 DSDM channels, and (b) constellations of core #16, wavelength #11 after 1644.8 km transmission.

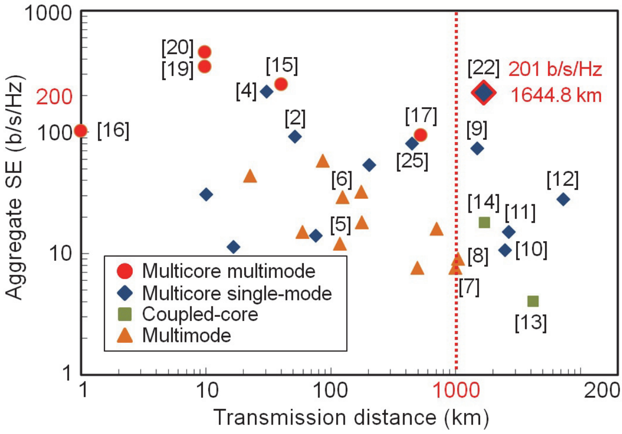

Fig. 8. Aggregate SE versus transmission distance of recent SDM-WDM experiments.

recovery. 0.75 M bits were used to calculate the BERs and Q-factors.

V. EXPERIMENTAL RESULTS

1) *Characteristics of the 32-core transmission line*

Figure 6 shows the span loss and worst inter-core crosstalk of the 32-core DSDM transmission line including the 51.4-km 32-core fiber, 32-channel FI/FO devices, and the 32-channel matrix switches measured at the center wavelength λ_{11}=1550.128 nm. The span loss for each spatial channel was derived from the power difference between signals input to input port #1 of the input-side 32-channel matrix switch and signals output from output port #1 of the output-side 32-channel matrix switch. The inter-core crosstalk was characterized by measuring the power of light output from output port #1 of the output-side 32-channel matrix switch when light was input only to the core under measurement relative to when light was input to all cores other than that of the core under measurement. The switch settings were changed from core #1 to #32 to measure the span loss and inter-core crosstalk for all 32 spatial channels. The span loss was around 1-2 dB higher than that of the 32-core fiber with FI/FO devices. This difference was caused by the insertion loss of the 32-channel matrix switches. The measured inter-core crosstalk of the transmission line with and without the 32-channel matrix switches was almost the same because of the low crosstalk of < -50 dB of the 32-channel matrix switches.

2) *Q-factor measurement results*

Figure 7(a) shows the measured Q-factors of the 20-DWDM PDM-16QAM signals after 1644.8 km transmission (=51.4 km × 32 loops) as a function of core number. We confirmed that the Q-factors for all 640 (20-DWDM × 32-DSDM) channels were above the Q-limit of 5.7 dB of LDPC convolutional codes using a layered decoding algorithm with 20 % FEC overhead [32]. Figure 7(b) shows an example constellation of the received signals for the center core #16, wavelength #11. The net data rate was 78.69 Gb/s, the SE was 6.295 b/s/Hz/core, and the aggregate SE was 201.46 b/s/Hz. Figure 8 shows the aggregate SE versus transmission distance of recent SDM-WDM experiments. The crosstalk-managed high-core count multi-core transmission line allowed us to transmit DSDM signals with high order modulation format over a long distance. We have thus successfully demonstrated a long-haul DSDM transmission over 1600 km with a high aggregate SE above 200 b/s/Hz.

In the above measurement, polarization scrambler was not included in the recirculating loop. To verify the effect of polarization for this experimental setup, a loop synchronous polarization scrambler was inserted in loop #1 after the amplifier and filter, and Q-factors were measured with and without the polarization scrambler. The measured Q-factors were almost the same, which confirmed that the measurement error due to polarization was negligible for our transmission line.

3) *Q-penalty caused by inter-core crosstalk*

To evaluate the effect of inter-core crosstalk on transmission performance, we investigated the Q-penalty caused by inter-core crosstalk. Figure 9 shows the Q-penalty measured after 1644.8 km transmission at the center wavelength λ_{11} versus core number, where the Q-penalty was obtained by measuring the difference of the Q-factors when signal was input only to the core under measurement, and when signals were input to all 32-cores. The inner cores tend to have higher Q-penalty than the outer cores because they are subject to higher crosstalk from larger number of neighboring cores. To observe the effect of inter-core crosstalk on Q-factor more clearly, Figure 10 plots the Q-penalty versus inter-core crosstalk after 32-loops estimated from the span crosstalk shown in Fig. 6. There is strong correlation between the Q-factor and inter-core crosstalk, with Q-penalty increasing linearly as a function of inter-core crosstalk. Highest Q-penalties of 1.2 and 1.0 dB were observed with cores #27 and #28, respectively. If we are to use the core-averaging scheme,

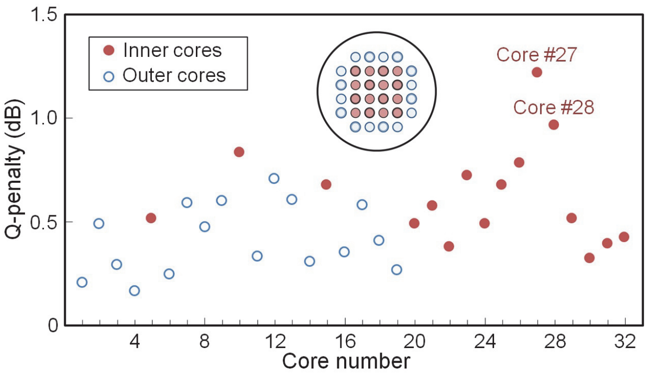

Fig. 9. Measured Q-penalty after 1644.8 km transmission at the center wavelength versus core number.

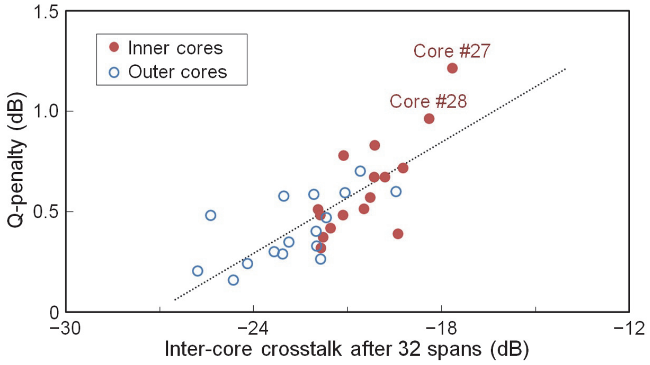

Fig. 10. Correlation between Q-penalty and inter-core crosstalk after 32-loops estimated from the span crosstalk of each core.

the crosstalk after the series of 32-cores will add up to -21 dB and will result in a Q-penalty of 0.55 dB. This estimate is 0.65 dB lower than that of the actually obtained worst Q-penalty of 1.2 dB in core #27, thus indicating the significance of characterizing the performance of each core.

Figure 11 shows the measured Q-factor as a function of transmission distance for these two cores #27 and #28 with the largest Q-penalties. The blank plots are the Q-factor measured when the signal was input only to the core under measurement and all other 31 cores contained no signal (measurement without inter-core crosstalk). The back-to-back performance of the 96 Gb/s PDM-16QAM was approximately 12 dB. Figure 12 shows the system optical signal-to-noise ratio (OSNR) as a function of transmission distance. 50 GHz-spaced five WDM continuous wave (CW) light with the launch power equivalent to that of the transmission signal was input to the recirculating loop system. The system OSNR was measured at various loops by an optical spectrum analyzer with 0.1 nm resolution, and converted to the OSNR of the 12.5 GHz-spaced 20-DWDM signals. The Q-factor degradation with transmission distance in Fig. 11 was caused by the OSNR degradation as well as nonlinearity and other impairments of the system.

The filled plots in Fig. 11 are the Q-factor measured when the signal was input to all 32 cores (measurement with inter-core crosstalk). The Q-factor difference between the filled and blank plots at each transmission distance corresponds to the Q-factor penalty caused by the inter-core crosstalk. The figure also indicates that the Q-factor performance over long distances for both cores #27 and #28 were similar, although these two cores had different refractive index profiles. This result confirms that the heterogeneous design has no detrimental effect on the transmission performance, and is useful for extending reach by crosstalk reduction.

The dotted line shows the Q-factor limit of 5.7 dB for 20 % FEC overhead [32]. By implementing the latest digital signal processing, longer distance is possible. Suppose we use 25.5 % FEC overhead [33], the Q-factor limit will relax to 5 dB, and yield approximately 10 % increase of transmission distance with a slightly reduced aggregate SE of 192.63 b/s/Hz.

4) Recirculating and non-recirculating crosstalk signals

In standard long distance MCF transmission experiments, recirculating signals are loaded to all cores, and transmitted together with the core under measurement to approximate transmission over a long transmission line. This is under the assumption that the transmission performance may differ between recirculating and non-recirculating crosstalk signals. To approximate a full parallel recirculating loop system, we have loaded recirculating signals to four adjacent cores in the diagonal position relative to the core under measurement which is assumed to affect the core under measurement the most during transmission due to inter-core crosstalk.

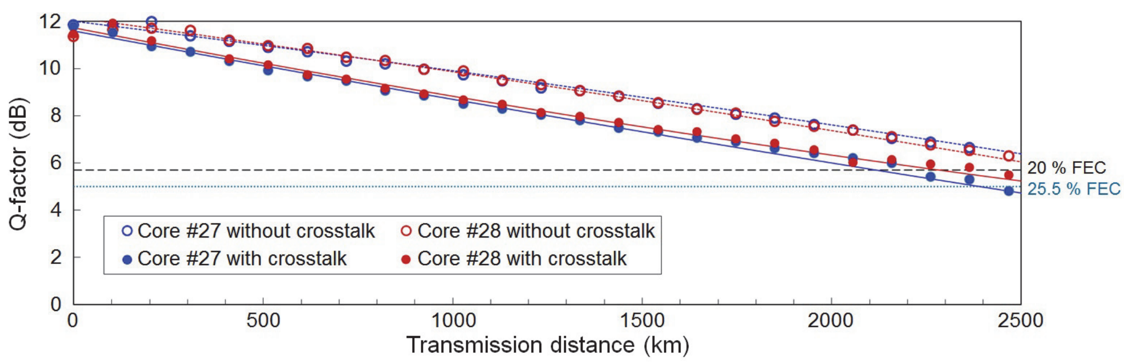

Fig. 11. Measured Q-factor as a function of transmission distance for cores #27 and #28 with and without inter-core crosstalk. A 5.7 dB Q-limit of 20 % FEC overhead was employed in this transmission experiment.

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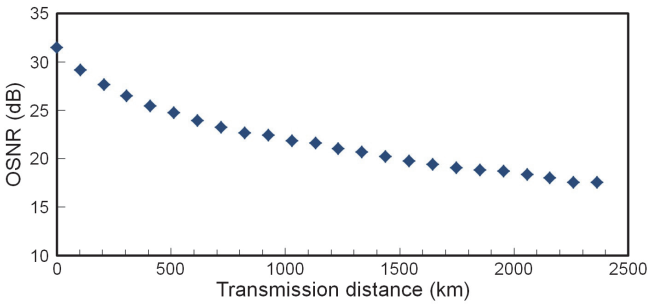

Fig. 12. System OSNR as a function of transmission distance.

In this section, we compare the difference of Q-factors when the neighboring cores are changed from recirculating signals to non-recirculating signals. The type of signals loaded to cores was controlled by changing the port connections of the 32-channel matrix switches. Figure 13 shows the signal loading pattern including, (a) recirculating signals loaded to four diagonal cores, (b) non-recirculating signals loaded to four diagonal cores, (c) non-recirculating signals loaded to four nearest cores, (d) recirculating signals loaded to four nearest cores, (e) recirculating signals loaded to four diagonal cores and non-recirculating signals loaded to all other 27 cores (same crosstalk loading pattern as the Q-factor measurement in Fig. 7), and (e) non-recirculating signals loaded to all other 31 cores. Recirculating signal for loop #1 was always loaded to the core under measurement.

Figures 14(a) and (b) shows the Q-factor difference as a function of transmission distance for core #27 and #28, respectively, measured at the center wavelength λ_{11}. The OSNR level of the input signal was 31.5 dB, and that after 32 loops was 19.4 dB (Fig. 12). The Q-factor difference designated as “diagonal cores” are the difference of the measured Q-factors when signals were loaded into five cores with the pattern in Fig. 13 (a) between that in Fig. 13 (b). Similarly, those designated as “nearest cores” are the difference of the measured Q-factors when signals were loaded into five cores with the pattern in Fig. 13 (c) between that in Fig. 13 (d). The difference of the measured Q-factors when signals were loaded into all the 32 cores with the pattern in Fig. 13 (e) between that in Fig. 13 (f) are designated as “all cores”. With various distances, the Q-factor difference was within measurement error. This result implies that in our experimental setup, the transmission performance is the same regardless of the neighboring cores being recirculating or non-recirculating crosstalk signals. The conditions necessary for such state include managing the experimental setup to launch all cores with uniform signal input power, and to maintain similar overall passband spectrum for the recirculating and non-recirculating crosstalk signals.

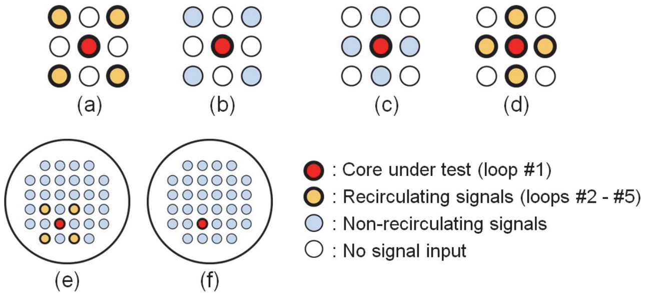

Fig. 13. Crosstalk loading patterns employed to compare the difference of the effect of recirculating and non-recirculating crosstalk signals on the core under measurement. Recirculating signals from loop #1 was loaded to core under test, various signals was input to other cores including (a) recirculating signals loaded to four diagonal cores, (b) non-recirculating signals loaded to four diagonal cores, (c) recirculating signals loaded to four nearest cores, (d) non-recirculating signals loaded to four nearest cores, (e) recirculating signals loaded to four diagonal cores and non-recirculating signals loaded to all other 27 cores, and (e) non-recirculating signals loaded to all other 31 cores.

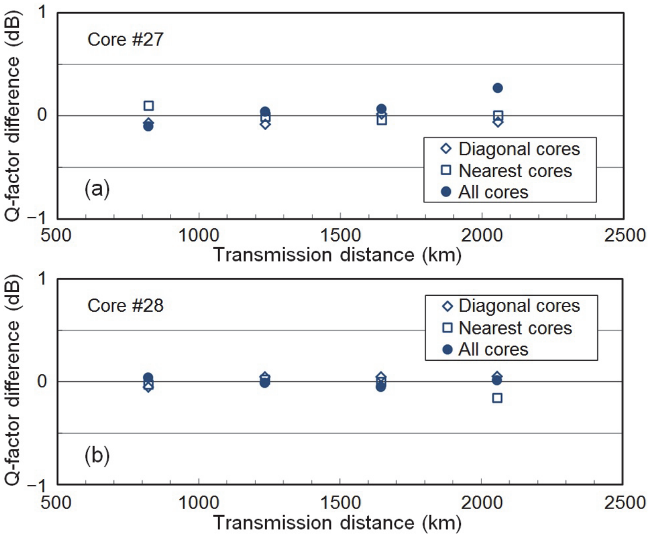

Fig. 14. Difference of measured Q-factors with recirculating and non-recirculating crosstalk signals for (a) core #27 and (b) core #28. The “diagonal cores”, “nearest cores”, and “all cores” show difference of Q-factors between crosstalk loading patterns in Figs. 13(a) and (b), Figs. 13(c) and (d), and Figs. 13(e) and (f), respectively.

VI. CONCLUSION

We have presented the experimental demonstration of a long-haul DSDM transmission over a 32-core single-mode transmission line. We have provided the characteristics of the novel low-crosstalk heterogeneous 32-core fiber and the configuration of the novel partial recirculating loop system. The low span crosstalk of −34.5 dB/51.4 km realized by our fiber design and fabrication technology enabled us to achieve long-haul DSDM unidirectional transmission over a thousand km with over 30 spatial multiplicity for the first time. The 12.5GHz-spaced 20-DWDM, PDM-16QAM signals over 32-cores yielded a high aggregate spectral efficiency of 201.46 b/s/Hz. The transmission distance of 1644.8 km equivalent to 32 loops of the 51.4 km span is more than three times longer for DSDM transmission with over 30 spatial multiplicity, and around three times larger spatial multiplicity per direction for long-haul transmission exceeding 1000 km. In addition, we investigated the effect of crosstalk on Q-penalty utilizing the partial recirculating loop system, and showed that the Q-penalty had strong correlation with inter-core crosstalk, and depended on core allocation. Moreover, we examined the validity of the measurement using the partial recirculating loop system. As an alternative to conventional multicore recirculating loop measurement, our proposed partial recirculating loop system is an effective means for characterizing long distance transmission performance of multicore transmission lines, in particular, when the number of cores is large and when inter-core crosstalk depend on core configuration.

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