# Long-Haul Dense Space-Division Multiplexed Transmission Over Low-Crosstalk Heterogeneous 32-Core Transmission Line Using a Partial Recirculating Loop System

Takayuki Mizuno, *Member, IEEE*, Kohki Shibahara*, Member, IEEE, Member, OSA*, Feihong Ye, Yusuke Sasaki, Yoshimichi Amma, Katsuhiro Takenaga, Yongmin Jung*, Member, IEEE*, Klaus Pulverer, Hirotaka Ono*, Senior Member, IEEE, Senior Member, OSA*, Yoshiteru Abe, Makoto Yamada*, Senior Member, IEEE*, Kunimasa Saitoh*, Member, IEEE, Member, OSA*, Shoichiro Matsuo*, Member, IEEE, Member, OSA*, Kazuhiko Aikawa, Marc Bohn, David J. Richardson*, Fellow, IEEE, Fellow, OSA*, Yutaka Miyamoto*, Member, IEEE*, and Toshio Morioka*, Member, IEEE, Fellow, OSA*

*(Post-Deadline)*

***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 1000 km. We demonstrate 32-core DSDM 20 wavelength-division-multiplexed 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 intercore crosstalk.**

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

T. Mizuno, K. Shibahara, and Y. Miyamoto are with the NTT Network Innovation Laboratories, NTT Corporation, Yokosuka 239-0847, Japan (email: mizuno.takayuki@lab.ntt.co.jp; shibahara.kouki@lab.ntt.co.jp; miyamoto.yutaka@lab.ntt.co.jp).

F. Ye and T. Morioka are with the DTU Fotonik, Technical University of Denmark, Kgs. Lyngby DK2800, Denmark (email: feye@fotonik.dtu.dk; tomo@fotonik.dtu.dk).

Y. Sasaki, Y. Amma, K. Takenaga, S. Matsuo, and K. Aikawa are with the Fujikura Ltd., Sakura 285-8550, Japan (email: yusuke.sasaki@jp.fujikura.com; yoshimichi.amma@jp.fujikura.com; katsuhiro.takenaga@jp.fujikura.com; shoichiro.matsuo@jp.fujikura.com; kazuhiko.aikawa@jp.fujikura.com).

Y. Jung and D. J. Richardson are with the Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, U.K. (e-mail: ymj@orc.soton.ac.uk; djr@orc.soton.ac.uk)

K. Pulverer and M. Bohn are with the Coriant R&D GmbH, Munich, 81541, Germany (email: klaus.pulverer@coriant.com; marc.bohn@coriant.com).

H. Ono and Y. Abe are with the NTT Device Technology Laboratories, NTT Corporation, Atsugi 243-0198, Japan (email: ono.hirotaka@lab.ntt.co.jp; abe.yoshiteru@lab.ntt.co.jp).

M. Yamada is with the Osaka Prefecture University, Osaka 599-8531, Japan (email: myamada@eis.osakafu-u.ac.jp).

K. Saitoh is with the Graduate School of Information Science and Technology, Hokkaido University, Sapporo 060-0814, Japan (email: ksaitoh@ist.hokudai.ac.jp).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JLT.2016.2615070

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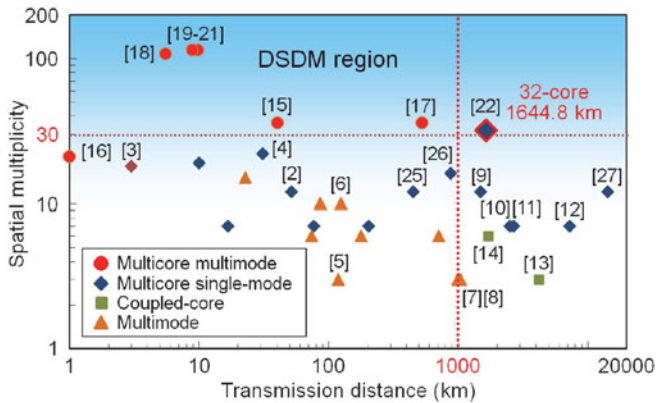
Fig. 1. Spatial multiplicity as a function of distance in recent SDM experiments.

plicity factor of more than 60 [21]. Although these reports 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 $(A_{\mathrm{eff}})$, 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.

## 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 in-
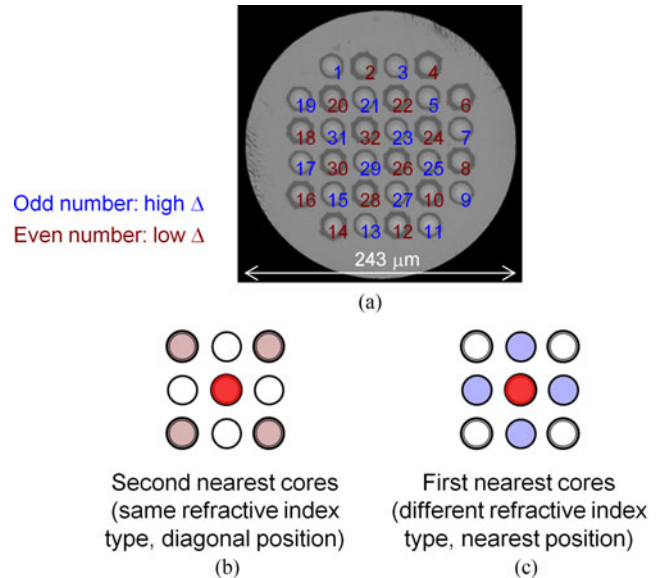


Fig. 2. (a) Cross sectional view of the heterogeneous 32-core single-mode MCF, (b) four cores in the diagonal position with the same refractive index type relative to the center core, and (c) four cores in the nearest position with the different refractive index type relative to the center core.
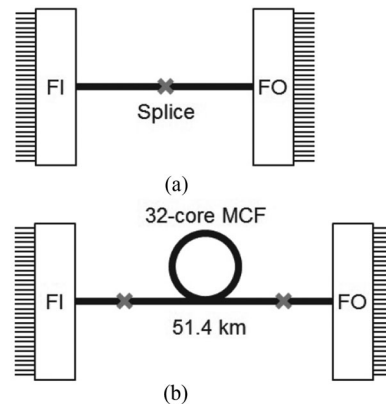


Fig. 3. Schematic diagram showing the components and splicing points for (a) measuring the characteristics of the free-space optics based 32-channel FI/FO devices, and (b) constructing the 32-core DSDM transmission line.

dex 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 $\mu$m, respectively, typical for an MCF. The fiber length was 9.6 and 11.0 km, and the $A_{\mathrm{eff}}$ at 1550 nm was 77 and 75 $\mu$m$^2$, 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.
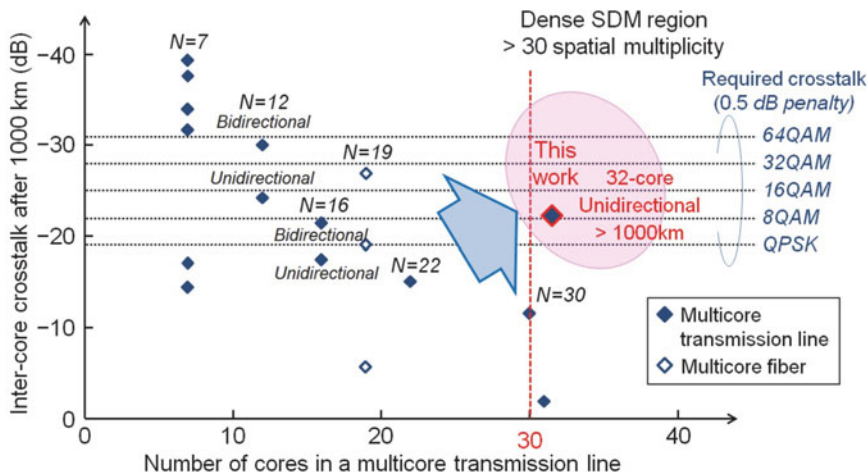
Fig. 4. Crosstalk after 1000-km transmission as a function of the number of core per fiber in a single-mode MCF. The filled and blank plot shows characteristics of multicore transmission line including FI/FO devices and multicore fiber, respectively. Dotted lines show the crosstalk levels required for various modulation formats assuming 0.5 dB penalty.

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. Fig. 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 $\mu$m, and the cladding diameter was 243 $\mu$m. The cutoff wavelength at a length of 1 km was <1.53 $\mu$m. The attenuation and the $A_{\text{eff}}$ at 1550 nm was 0.24 dB/km and > 80.3 $\mu$ m$^2$, 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 de-

vices were <14.1 dB/ span and <−34.5 dB/span at 1550 nm, respectively.

Fig. 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 I. Various experimental setups have been employed for approximating long distance MCF transmission line. The commonly used 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

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/500 km | 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 |

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 Fig. 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 sig-

nals 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.

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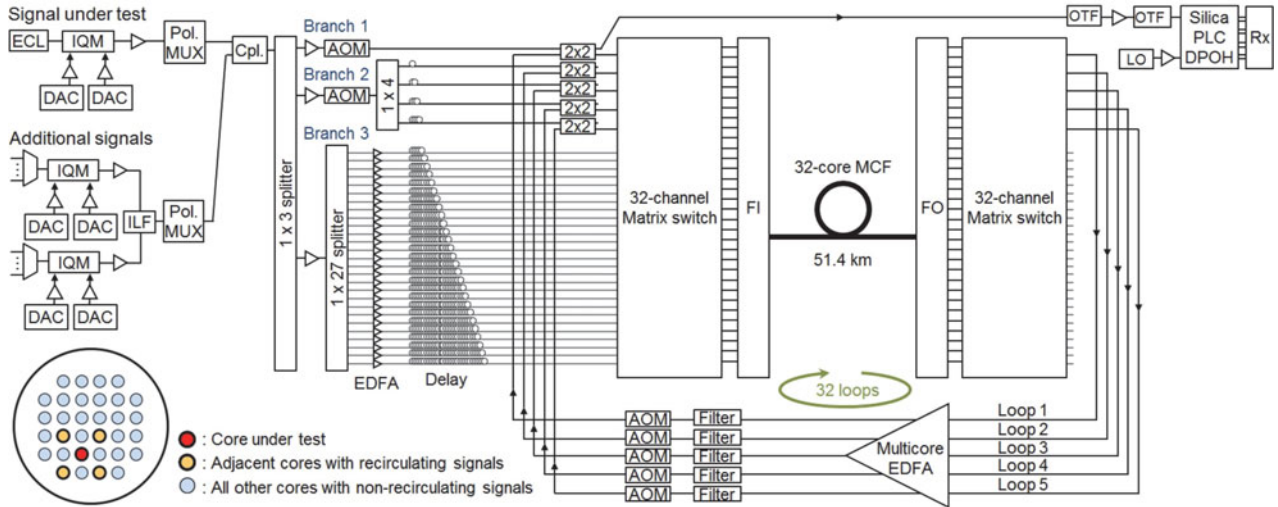
Fig. 5.    Experimental setup with a novel partial recirculating loop system.

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, $\Delta t$, $2\Delta t$, ..., and $31\Delta t$ with a unit time delay $\Delta t$ 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. 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 $2 \times 2$ frequency domain equalization (FDE) combined with phase recovery. 0.75 M bits were used to calculate the BERs and Q-factors.

## V. Experimental Results

### A. Characteristics of the 32-Core Transmission Line

Fig. 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 $\lambda_{11} =$ 1550.128 nm. The span loss for each spatial channel was de-
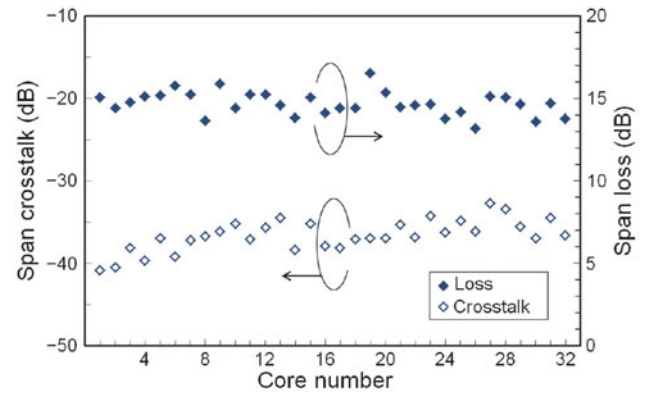


Fig. 6.    Span crosstalk and loss of the DSDM transmission line measured at the center wavelength, including 51.4-km 32-core fiber, 32-channel FI/FO devices, and 32-channel matrix switches.

rived 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.

### B. Q-Factor Measurement Results

Fig. 7(a) shows the measured Q-factors of the 20-DWDM PDM-16QAM signals after 1644.8 km transmission ( = 51.4 km $\times$ 32 loops) as a function of core number. We confirmed that the Q-factors for all 640 (20-DWDM $\times$ 32-DSDM) channels were
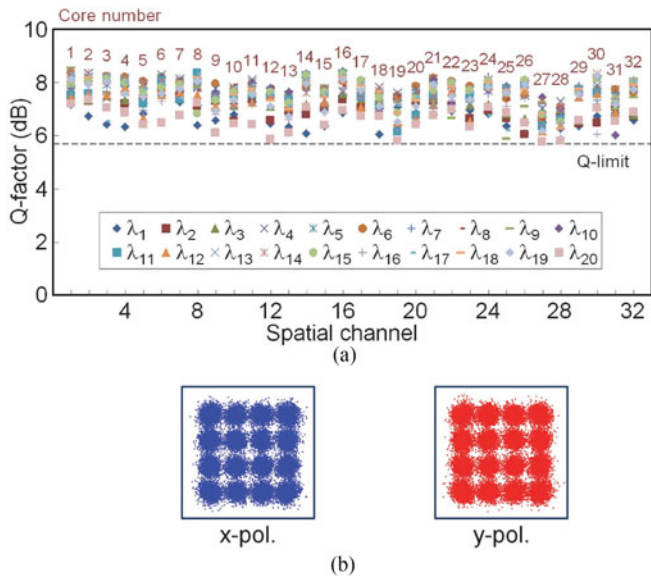
Fig. 7. Measured (a) Q-factors for 20 DWDM × 32 DSDM channels, and (b) constellations of core #16, wavelength #11 after 1644.8 km transmission.
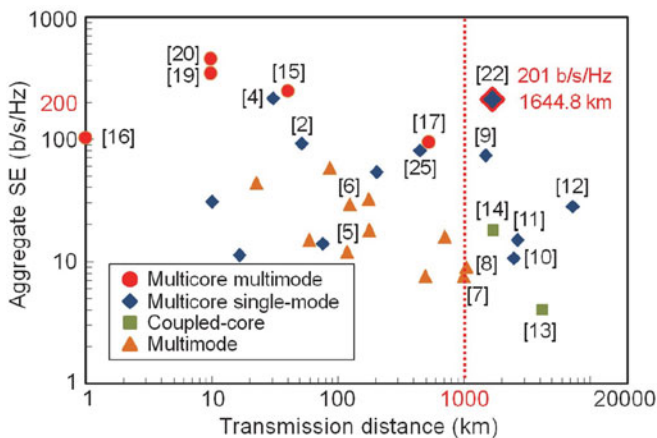


Fig. 8. Aggregate SE versus transmission distance of recent SDM-WDM experiments.
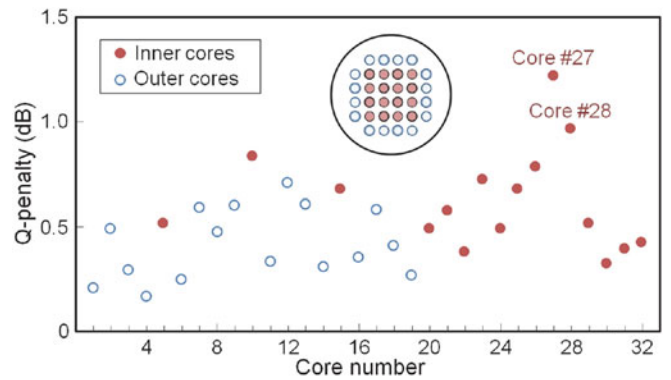


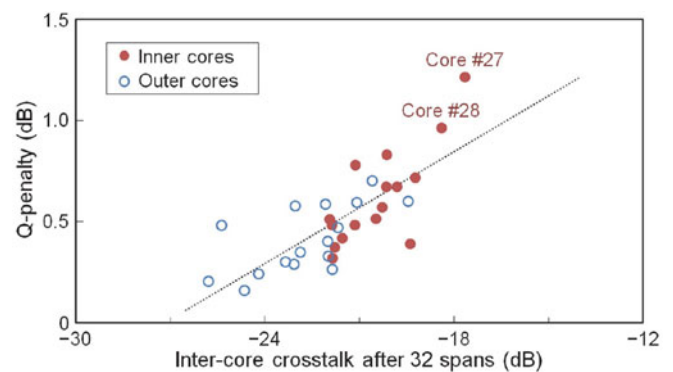Fig. 9. Measured Q-penalty after 1644.8 km transmission at the center wavelength versus core number.



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

above the Q-limit of 5.7 dB of LDPC convolutional codes using a layered decoding algorithm with 20% FEC overhead [32]. Fig. 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. Fig. 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.

### C. 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. Fig. 9 shows the Q-penalty measured after 1644.8 km transmission at the center wavelength $\lambda_{11}$ 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, Fig. 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, 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
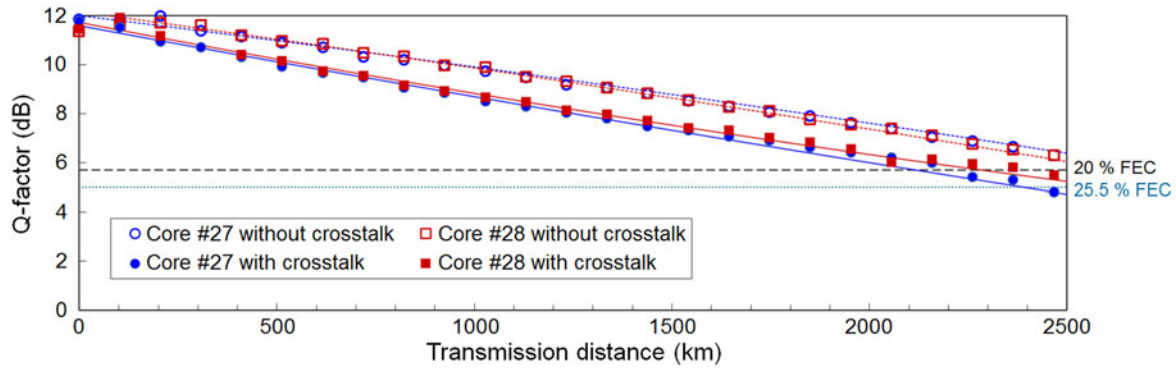
Fig. 11. Measured Q-factor as a function of transmission distance for cores #27 and #28 with and without inter-core crosstalk. A 5.7 dB Q-limit of 20% FEC overhead was employed in this transmission experiment.
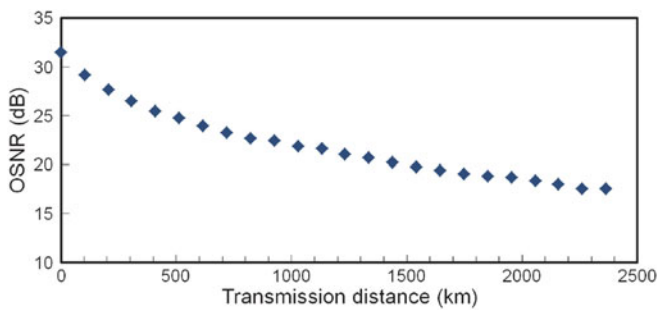


Fig. 12. System OSNR as a function of transmission distance.

1.2 dB in core #27, thus indicating the significance of characterizing the performance of each core.

Fig. 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. Fig. 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.

### D. 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.

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. Fig. 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 (f) non-recirculating signals loaded to all other 31 cores. Recirculating signal for loop #1 was always loaded to the core under measurement.

Fig. 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 $\lambda_{11}$. The OSNR level of the input signal was 31.5 dB, and that after 32 loops was
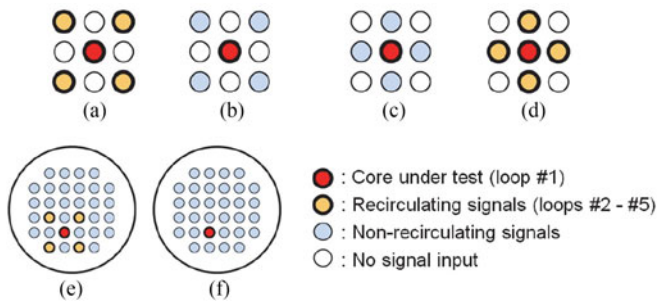
Fig. 13. Crosstalk loading patterns employed to compare the difference of the effect of recirculating and non-recirculating crosstalk signals on the core under measurement. Recirculating signals from loop #1 was loaded to core under test, various signals was input to other cores including (a) recirculating 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 (f) non-recirculating signals loaded to all other 31 cores.
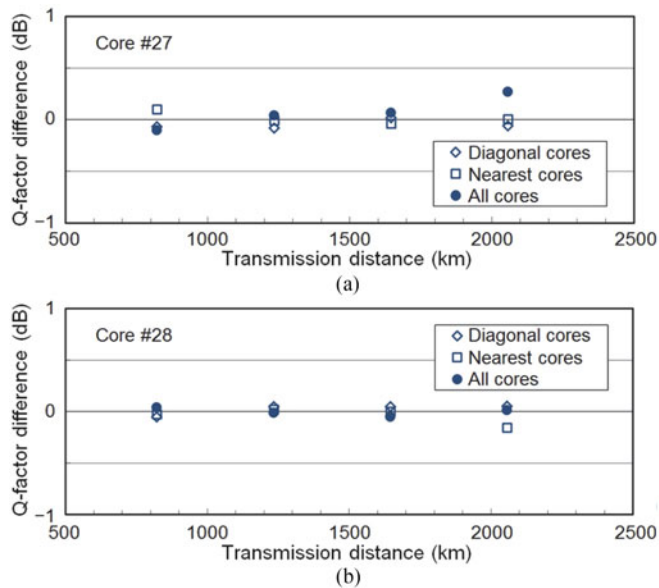


Fig. 14. Difference of measured Q-factors with recirculating and non-recirculating crosstalk signals for (a) core #27 and (b) core #28. The "diagonal cores", "nearest cores", and "all cores" show difference of Q-factors between crosstalk loading patterns in Figs. 13(a) and (b), Figs. 13(c) and (d), and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

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.

## 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.

## ACKNOWLEDGMENT

## REFERENCES

[1] T. Morioka, "New generation optical infrastructure technologies: "EXAT initiative" towards 2020 and beyond," in *Proc. OptoElectron. Commun. Conf.*, 2009, pp. 1–2.

[2] H. Takara, A. Sano, T. Kobayashi, H. Kubota, H. Kawakami, A. Matsuura, Y. Miyamoto, Y. Abe, H. Ono, K. Shikama, Y. Goto, K. Tsujikawa, Y. Sasaki, I. Ishida, K. Takenaga, S. Matsuo, K. Saitoh, M. Koshiba, and T. Morioka, "1.01-Pb/s (12 SDM/222 WDM/456 Gb/s) crosstalk-managed transmission with 91.4-b/s/Hz aggregate spectral efficiency," in *Proc. Eur. Conf. Exhib. Opt. Commun.*, 2012, Paper Th.3.C.1.

[3] D. Qian, E. Ip, M.-F. Huang, M.-J. Li, A. Dogariu, S. Zhang, Y. Shao, Y.-K. Huang, Y. Zhang, X. Cheng, Y. Tian, P. N. Ji, A. Collier, Y. Geng, J. Liares, C. Montero, V. Moreno, X. Prieto, and T. Wang, "1.05Pb/s transmission with 109 b/s/Hz spectral efficiency using hybrid single- and few-mode cores," in *Proc. Frontiers Opt./Laser Sci. Conf.*, 2012, Paper FW6C.3.

[4] B. J. Puttnam, R. S. Luís, W. Klaus, J. Sakaguchi, J.-M. Delgado Mend-inueta, Y. Awaji, N. Wada, Y. Tamura, T. Hayashi, M. Hirano, and J. Marciante, "2.15 Pb/s transmission using a 22 core homogeneous single-mode multi-core fiber and wideband optical comb," in *Proc. Eur. Conf. Opt. Commun.*, 2015, Paper PDP.3.1.

[5] V. A. J. M. Sleiffer, Y. Jung, V. Veljanovski, R. G. H. van Uden, M. Kuschnerov, Q. Kang, L. Grner-Nielsen, Y. Sun, D. J. Richardson, S. Alam, F. Poletti, J. K. Sahu, A. Dhar, H. Chen, B. Inan, A. M. J. Koonen, B. Corbett, R. Winfield, A. D. Ellis, and H. de Waardt, "73.7 Tb/s (96 × 3 × 256-Gb/s) mode-division-multiplexed DP-16QAM transmission with inline MM-EDFA," in *Proc. Eur. Conf. Exhib. Opt. Commun.*, 2012, Paper Th.3.C.4.

[6] R. Ryf, H. Chen, N. K. Fontaine, A. M. Velazquez-Bentez, Jose Antonio-Lopez, C. Jin, B. Huang, M. Bigot-Astruc, D. Molin, F. Achten, P. Sillard, and R. Amezcua-Correa, "10-mode mode-multiplexed transmission over 125-km single-span multimode fiber," in *Proc. Eur. Conf. Opt. Commun.*, 2015, Paper PDP.3.3.

[7] E. Ip, M.-J. Li, K. Bennett, Y.-K. Huang, A. Tanaka, A. Korolev, K. Koreshkov, W. Wood, E. Mateo, J. Hu, and Y. Yano, "146λ × 6 × 19-Gbaud wavelength- and mode-division multiplexed transmission over 10 × 50-km spans of few-mode fiber with a gain-equalized few-mode EDFA," in *Proc. Opt. Fiber Commun. Conf. Expo./Nat. Fiber Opt. Eng. Conf.*, 2013, Paper PDP5A.2.

[8] R. Ryf, M. Esmaeelpour, N. K. Fontaine, H. Chen, A. H. Gnauck, R.-J. Essiambre, J. Toulouse, Y. Sun, and R. Lingle, Jr., "Distributed Raman amplification based transmission over 1050-km few-mode fiber," in *Proc. Eur. Conf. Opt. Commun.*, 2015, Paper Tu.3.2.3.

[9] T. Kobayashi, H. Takara, A. Sano, T. Mizuno, H. Kawakami, Y. Miyamoto, K. Hiraga, Y. Abe, H. Ono, M. Wada, Y. Sasaki, I. Ishida, K. Takenaga, S. Matsuo, K. Saitoh, "2 × 344 Tb/s propagation-direction interleaved transmission over 1500-km MCF enhanced by multicarrier full electric-field digital back-propagation," in *Proc. Eur. Conf. Exhib. Opt. Commun.*, 2013, Paper PD3.E.4.

[10] K. Takeshima, T. Tsuritani, Y. Tsuchida, K. Maeda, T. Saito, K. Watanabe, T. Sasa, K. Imamura, R. Sugizaki, K. Igarashi, I. Morita, and M. Suzuki, "51.1-Tbit/s MCF transmission over 2, 520 km using cladding pumped 7-core EDFAs," in *Proc. Opt. Fiber Commun. Conf. Exhib.*, 2015, Paper W3G.1.

[11] S. Chandrasekhar, A. H. Gnauck, Xiang Liu, P. J. Winzer, Y. Pan, E. C. Burrows, T. F. Taunay, B. Zhu, M. Fishteyn, M. F. Yan, J. M. Fini, E.M. Monberg, and F. V. Dimarcello, "WDM/SDM transmission of 10 × 128-Gb/s PDMQPSK over 2688-km 7-core fiber with a per-fiber net aggregate spectral-efficiency distance product of 40, 320 km b/s/Hz," *Opt. Express*, vol. 20, no. 2, pp. 706–711, Jan. 2012.

[12] K. Igarashi, T. Tsuritani, I. Morita, Y. Tsuchida, K. Maeda, M. Tadakuma, T. Saito, K. Watanabe, K. Imamura, R. Sugizaki, and M. Suzuki, "1.03-Exabit/s × km super-Nyquist-WDM transmission over 7, 326-km seven-core fiber," in *Proc. Eur. Conf. Exhib. Opt. Commun.*, 2013, Paper PD3.E.3.

[13] R. Ryf, R.-J. Essiambre, A. H. Gnauck, S. Randel, M. A. Mestre, C. Schmidt, P. J. Winzer, R. Delbue, P. Pupalaikis, A. Sureka, T. Hayashi, T. Taru, and T. Sasaki, "Space-division multiplexed transmission over 4200-km 3-core microstructured fiber," in *Proc. Opt. Fiber Commun. Conf. Expo./Nat. Fiber Opt. Eng. Conf.*, 2012, Paper PDP5C.2.

[14] R. Ryf, N. K. Fontaine, B. Guan, R.-J. Essiambre, S. Randel, A. H. Gnauck, S. Chandrasekhar, A. Adamiecki, G. Raybon, B. Ercan, R. P. Scott, S. J. Ben Yoo, T. Hayashi, T. Nagashima, and T. Sasaki, "1705-km transmission over coupled-core fibre supporting 6 spatial modes," in *Proc. Eur. Conf. Opt. Commun.*, 2014, Paper PD.3.2.

[15] T. Mizuno, T. Kobayashi, H. Takara, A. Sano, H. Kawakami, T. Nakagawa, Y. Miyamoto, Y. Abe, T. Goh, M. Oguma, T. Sakamoto, Y. Sasaki, I. Ishida, K. Takenaga, S. Matsuo, K. Saitoh, and T. Morioka, "12-core × 3-mode dense space division multiplexed transmission over 40 km employing multi-carrier signals with parallel MIMO equalization," in *Proc. Opt. Fiber Commun. Conf. Exhib.*, 2014, Paper Th5B.2.

[16] R. G. H. van Uden, R. A. Correa, E. A.-Lopez, F. M. Huijskens, G. Li, A. Schulzgen, H. de Waardt, A. M. J. Koonen, and C. M. Okonkwo, "1 km hole-assisted few-mode multi-core fiber 32QAM WDM transmission," in *Proc. Eur. Conf. Opt. Commun.*, 2014, Paper Mo.3.3.4.

[17] K. Shibahara , T. Mizuno, H. Takara, A. Sano, H. Kawakami, D. Lee, Y. Miyamoto, H. Ono, M. Oguma, Y. Abe, T. Kobayashi, T. Matsui , R. Fukumoto, Y. Amma, T. Hosokawa, S. Matsuo, K. Saito, H. Nasu, and T. Morioka, "Dense SDM (12-core × 3-mode) transmission over 527 km with 33.2-ns mode-dispersion employing low-complexity parallel MIMO frequency-domain equalization," in *Proc. Opt. Fiber Commun. Conf. Exhib.*, 2015, Paper Th5C.3.

[18] J. Sakaguchi, W. Klaus, J.-M. D. Mendinueta, B. J. Puttnam, R. S. Luis, Y. Awaji, N. Wada, T. Hayashi, T. Nakanishi, T. Watanabe, Y. Kokubun, T. Takahata, and T. Kobayashi, "Realizing a 36-core, 3-mode fiber with 108 spatial channels," in *Proc. Opt. Fiber Commun. Conf. Exhib.*, 2015, Paper Th5C.2.

[19] K. Igarashi, D. Souma, Y. Wakayama, K. Takeshima, Y. Kawaguchi, T. Tsuritani, and I. Morita, "114 space-division-multiplexed transmission over 9.8-km weakly-coupled-6-mode uncoupled-19-core fibers," in *Proc. Opt. Fiber Commun. Conf. Exhib.*, 2015, Paper Th5C.4.

[20] D. Soma, K. Igarashi, Y. Wakayama, K. Takeshima, Y. Kawaguchi, N. Yoshikane, T. Tsuritani, I. Morita, and M. Suzuki, "2.05 peta-bit/s super-Nyquist-WDM SDM transmission using 9.8-km 6-mode 19-core fiber in full C band," in *Proc. Eur. Conf. Opt. Commun.*, 2015, Paper PDP.3.2.

[21] T. Sakamoto, T. Matsui, K. Saitoh, S. Saitoh, K. Takenaga, T. Mizuno, Y. Abe, K. Shibahara, Y. Tobita, S. Matsuo, K. Aikawa, S. Aozasa, K. Naka-jima, and Y. Miyamoto, "Low-loss and low-DMD few-mode multi-core fiber with highest core multiplicity factor," in *Proc. Opt. Fiber Commun. Conf. Exhib.*, 2016, Paper Th5A.2.

[22] T. Mizuno, K. Shibahara, H. Ono, Y.Abe, Y. Miyamoto, F. Ye, T. Morioka, Y. Sasaki, Y. Amma, K. Takenaga, S. Matsuo, K. Aikawa, K. Saitoh, Y. Jung, D. J. Richardson, K. Pulverer, M. Bohn, and M. Yamada, "32-core dense SDM unidirectional transmission of PDM-16QAM signals over 1600 km using crosstalk-managed single-mode heterogeneous multicore transmission line," in *Proc. Opt. Fiber Commun. Conf. Exhib.*, 2016, Paper Th5C.3.

[23] S. Matsuo, K. Takenaga, Y. Sasaki, Y. Amma, S. Saito, K. Saitoh, T. Matsui, K. Nakajima, T. Mizuno, H. Takara, Y. Miyamoto, and T. Morioka, "High-spatial-multiplicity multicore fibers for future dense space-division-multiplexing systems," *J. Lightw. Technol.*, vol. 34, no. 6, pp. 1464–1475, Mar. 2016.

[24] K. Aikawa, Y. Sasaki, Y. Amma, K. Takenaga, S. Matsuo, K. Saitoh, T. Morioka, and Y. Miyamoto, "High core count single-mode multicore fiber for dense space division multiplexing," in *Proc. IEEE Photon. Soc. Summer Top. Meeting Series,* 2016, Paper WE2.2.

[25] Y. Tottori, T. Kobayashi, and M. Watanabe, "Low loss optical connection module for seven-core multicore fiber and seven single-mode fibers," *IEEE Photon. Technol. Lett.*, vol. 24, no. 21, pp. 1926–1928, Nov. 2012.

[26] P. Winzer, A. Gnauck, A. Konczykowska, F. Jorge, and J.-Y. Dupuy, "Penalties from in-band crosstalk for advanced optical modulation for-mats," in *Proc. Eur. Conf. Exhib. Opt. Commun.,* 2011, Paper Tu.5.B.7.

[27] A. Sano, H. Takara, T. Kobayashi, and Y. Miyamoto, "Crosstalk-managed high capacity long haul multicore fiber transmission with propagation-direction interleaving," *J. Lightw. Technol.*, vol. 32, no. 16, pp. 2771–2779, Aug. 2014.

[28] A. Sano, H. Takara, T. Kobayashi, H. Kawakami, H. Kishikawa, T. Naka-gawa, Y. Miyamoto, Y. Abe, H. Ono, K. Shikama, M. Nagatani, T. Mori, Y. Sasaki, I. Ishida, K. Takenaga, S. Matsuo, K. Saitoh, M. Koshiba, M. Yamada, H. Masuda, and T. Morioka, "409-Tb/s + 409-Tb/s crosstalk sup-pressed bidirectional MCF transmission over 450 km using propagation-direction interleaving," *Opt. Express*, vol. 21, no. 14, pp. 16777–16783, Jul. 2013.

[29] M. Arikawa, T. Ito, E. L. T. de Gabory, and K. Fukuchi, "Crosstalk re-duction using bidirectional signal assignment over square lattice structure 16-core fiber for gradual upgrade of SSMF-based lines," in *Proc. Eur. Conf. Opt. Commun.*, 2015, Paper Th.1.2.3.

[30] A. Turukhin, O. V. Sinkin, H. G. Batshon, H. Zhang, Y. Sun, M. Mazurczyk, C. R. Davidson, J.-X. Cai, M. A. Bolshtyansky, D. G. Foursa, and A. Pilipetskii, "105.1 Tb/s power-efficient transmission over 14, 350 km using a 12-core fiber," in *Proc. Opt. Fiber Commun. Conf. Exhib.,* 2016, Paper Th4C.1.

[31] K. Takenaga, K. Ichii, S. Matsuo, Y. Abe, H. Ono, M. Yamada, and H. Masuda, "Multicore EDF optimized for remotely pumped amplification system over multicore fiber," in *Proc. OptoElectron. Commun. Conf. 2013 Int. Conf. Photon. Switching,* 2013, Paper TuS1-2.

[32] D. Chang , F. Yu, Z. Xiao, N. Stojanovic, F. N. Hauske, Y. Cai, C. Xie, L. Li, X. Xu, Q. Xiong, "LDPC convolutional codes using layered decoding algorithm for high speed coherent optical transmission," in *Proc. Opt. Fiber Commun. Conf. Expo./Nat. Fiber Opt. Eng. Conf.,* 2012, Paper OW1H.4.

[33] K. Sugihara, Y. Miyata, T. Sugihara, K. Kubo, H. Yoshida, W. Mat-sumoto, and T. Mizuochi, "A Spatially-coupled type LDPC code with an NCG of 12 dB for optical transmission beyond 100 Gb/s," in *Proc. Opt. Fiber Commun. Conf. Expo./Nat. Fiber Opt. Eng. Conf.*, 2013, Paper OM2B.4.

**Takayuki Mizuno** (M'04) received the B.E. degree in applied physics, the M.E. degree in crystalline materials science, and the Dr. Eng. degree in quantum engineering, all from Nagoya University, Nagoya, Japan, in 1998, 2000, and 2007, respectively.

In 2000, he joined the NTT Photonics Laboratories, NTT Corporation, Kanagawa, Japan, where he was involved in the research and development of silica planar lightwave circuit optical waveguide devices, including arrayed-waveguide gratings, Mach–Zehnder interferometer-based filters and switches, and digital coherent demodulators for advanced modulation formats. He is currently a Senior Research Engineer at the NTT Network Innovation Laboratories, NTT Corporation. He is the author and/or coauthor of more than 80 journal and international conference papers, and holds more than 30 granted patents. His current research interests include space-division-multiplexed transmission technology for ultrahigh-capacity optical transport systems.

He is a member of the Institute of Electronics, Information, and Communication Engineers of Japan.

**Kohki Shibahara** received the B.S. degree in physics and the M.S. degree in geophysics from Kyoto University, Kyoto, Japan, in 2008 and 2010, respectively.

Since 2010, he has been with the NTT Network Innovation Laboratories, Yokosuka, Kanagawa, Japan. His current research interests include spatial division multiplexing transmission systems and advanced multiple-input and multiple-output signal processing. He is a member of the Institute of Electronics, Information and Communication Engineers of Japan.

**Feihong Ye** received the B.E. degree from the South China University of Technology, Guangzhou, China, in 2005, the M.Sc. degree in integrated circuit design engineering from the Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong, in 2010, double degrees (Scuola Superiore Sant'Anna, Pisa, Italy, and Osaka University, Suita, Japan) from Erasmus Mundus program in MAsters on Photonic NETworks engineering, in 2012, and the Ph.D. degree in space-division multiplexing for ultrahigh-capacity photonic transport beyond Pbit/s from the Technical University of Denmark, Kgs. Lyngby, Denmark, in 2016.

**Yusuke Sasaki** was born in Chiba, Japan, in 1986. He received the B.E. and M.E. degrees in electrical engineering from the Tokyo Institute of Technology, Tokyo, Japan, in 2008 and 2010, respectively.

In 2010, he joined Fujikura Ltd., Chiba, Japan, and has been involved in research and development of multicore fibers. He is a member of the Institute of Electronics, Information and Communication Engineers of Japan.

**Yoshimichi Amma** received the B.S. degree in 2010 and the M.S. degree in mechanical engineering from Yokohama National University, Yokohama, Japan, in 2012.

In 2012, he joined Fujikura Ltd., Chiba, Japan, where he has been involved in research and development of multicore fibers. He has attended ten conferences. He is a member of the Institute of Electronics, Information and Communication Engineers of Japan.

**Katsuhiro Takenaga** was born in Tochigi, Japan, in 1976. He received the B.S. degree from Shinshu University, Nagano, Japan, and the M.S. degree from Hokkaido University, Sapporo, Japan, in 1999 and 2001, respectively, both in physics.

In 2001, he joined Fujikura Ltd., Chiba, Japan, where he has been involved in research and development of optical fibers. He is a member of the Institute of Electronics, Information and Communication Engineers of Japan.

**Yongmin Jung** (M'13) was born in Jindo, South Korea. He received the B.S. degree in physics from Chung-Ang University, Seoul, South Korea, in 2003, and the M.S. and Ph.D. degrees in engineering of information and communications from the Gwangju Institute of Science and Technology, Gwangju, South Korea, in 2004 and 2008, respectively.

In March 2008, he joined the Optoelectronics Research Centre, University of Southampton, Southampton, U.K., where he is currently a Senior Research Fellow. His current research interests include the multimode fiber amplifiers and mode-division-multiplexed transmission over few mode fibers.

**Klaus Pulverer** received the Ph.D. degree in mathematical physics from the University of Oxford, Oxford, U.K.

After several years of research in mathematical modeling and numerical simulation at the Technical University of Munich, he joined Siemens and later Nokia Siemens Networks and Coriant to work in the fields of communication protocols, next-generation networks architectures, and optical access. He has been active in standardization since 2002, until 2008 as a Co-Chair of architecture in European Telecommunications Standards Institute Telecommunications and Internet Converged Services and Protocols for Advanced Networking, and afterward in Telecommunication Standardization Sector of the International Telecommunications Union and Full Service Access Network for optical access.

**Hirotaka Ono** (M'96–SM'15) received the B.S., M.S., and Ph.D. degrees in applied physics from Tohoku University, Sendai, Japan, in 1993, 1995, and 2004, respectively.

He joined the NTT Laboratories, Tokai, Japan, in 1995. From 2005 to 2006, he was a Visiting Research Fellow in the Optoelectronics Research Centre, University of Southampton, Southampton, U.K. He has been involved in research on optical fiber amplifiers, including L- and S-band erbium-doped fiber amplifiers. He has also undertaken research on highly nonlinear fiber devices, photonic crystal fibers, and wavelength-division multiplexing transmission systems. His current research interests include fiber and waveguide devices, including optical amplifiers, used for space-division multiplexing systems.

He is a member of the Institute of Electronic, Information and Communication Engineers of Japan and the Japan Society of Applied Physics.

**Yoshiteru Abe** received the B.E. degree in electrical engineering, the M.E. degree in electronic device engineering, and the Dr. Eng. degree in electrical engineering from Kyushu University, Fukuoka, Japan, in 1996, 1998, and 2005, respectively.

In 1998, he joined the Nippon Telegraph and Telephone Corporation Optoelectronics Laboratories, Ibaraki, Japan. He is currently with the NTT Device Technology Laboratories, NTT Corporation, Atsugi, Japan. His current research interest focuses on optical fiber connectors.

He is a member of the Institute of Electronics, Information and Communication Engineers of Japan.

**Makoto Yamada** (SM'14) received the B.S., M.E., and Ph.D. degrees in electrical engineering from the Technical University of Nagaoka, Niigata, Japan, in 1983, 1985, and 1998, respectively.

In 1985, he joined the NTT Laboratories, where he was involved in research on guided-wave optical devices. Since 1989, he has been involved in research on optical fiber amplifiers. In 2008, he joined Osaka Prefecture University, Sakai, Japan, where he has been a Professor since 2013. His research interests include design and control for optical amplifiers and other components in optical networks. He is a Senior Member of the Institute of Electronics, Information and Communication Engineers.


**Kunimasa Saitoh** (S'00–M'01) received the B.S., M.S., and Ph.D. degrees in electronic engineering from Hokkaido University, Sapporo, Japan, in 1997, 1999, and 2001, respectively.

From 1999 to 2001, he was a Research Fellow of the Japan Society for the Promotion of Science. From 2001 to 2005, he was a Research Associate in the Graduate School of Engineering, Hokkaido University. From 2005 to 2013, he was an Associate Professor in the Graduate School of Information Science and Technology, Hokkaido University, where he has been a Professor since 2013. He is the author of more than 170 research papers in refereed international journals and more than 210 refereed international conference presentations. His research interests include fiber optics, nanophotonics, integrated optical devices, and computer-aided design and modeling of guided-wave devices.

 He is a member of the Optical Society of America and the Institute of Electronics, Information and Communication Engineers (IEICE). From 2009 to 2010, he was a Secretary/Treasurer of the IEEE Sapporo Section. He received the Excellent Paper Award and the Young Scientist Award from the IEICE in 1999 and 2002, respectively, the Young Scientists' Prize of the Commendation for Science and Technology from the Ministry of Education, Culture, Sports, Science, and Technology, Government of Japan in 2008, and the Japan Society for the Promotion of Science (JSPS) Prize from the JSPS in 2015.


**Shoichiro Matsuo** (M'11) received the B.E. and M.E. degrees in electrical engineering from Kyushu University, Fukuoka, Japan, in 1988 and 1990, respectively, and the Ph.D. degree in production and information science from Utsunomiya University, Tochigi, Japan, in 2008.

Since 1990, he has been with Fujikura Ltd., Japan, working on the research and development of transmission fibers for long-haul networks and FTTH networks as well as rare-earth-doped fibers and photonic bandgap fibers, and the manufacturing technology for these optical fibers. He was the General Manager of Laboratory, Fujikura Ltd., from April 2013 to October 2015. He is currently the General Manager of both the Optical Fiber Development Department and the Suzuka Optical Fiber Production Department, Fujikura Ltd.

He is a member of the Optical Society of America, the Japanese Society of Applied Physics, and the Institute of Electronics, Information and Communication Engineers.


**Kazuhiko Aikawa** received the B.S. degree in applied chemistry from Keio University, Tokyo, Japan, in 1990, and the Ph.D. degree in production and information science from Utsunomiya University, Utsunomiya, Japan, in 2010.

In 1990, he joined Fujikura Ltd., and was working on specialty optical fibers and optical components. He is currently the General Manager of Optical Communication Research Department, Advanced Technology Laboratory, Fujikura Ltd.


**Marc Bohn** received the Dipl.Ing. degree in electrical engineering and the Ph.D. degree from the University of Kiel, Chair for Communications, Kiel, Germany, in 1999 and 2005, respectively. He was with Siemens, Nokia Siemens Networks, and Coriant, Munich, Germany, working on transmission aspects in optical communications in different research and development and management functions. Since 2013, he has been the Head of the Research and Technology Department, Coriant. He has published more than 30 articles, including peer-reviewed journals, contributed and invited conference publications.


**David J. Richardson** (F'15) received the B.Sc. and Ph.D. degrees in fundamental physics from Sussex University, Brighton, U.K., in 1985 and 1989, respectively.

He joined the Optoelectronics Research Centre (ORC), Southampton University, Southampton, U.K., in 1989. He is currently the Deputy Director of the ORC with responsibility for the ORC's fiber-related activities. He is a prominent figure in the international photonics community and has published more than 900 conference and journal papers and produced more than 20 patents. His current research interests include amongst others: optical fiber communications, microstructured optical fibers, and pulsed high-power fiber lasers.

He is a Fellow of the Optical Society of America, the Institute of Engineering and Technology, and was made a Fellow of the Royal Academy of Engineering in 2009. He received the Royal Society University Fellowship in 1991 in recognition of his pioneering work on short-pulsed fiber lasers.


**Yutaka Miyamoto** (M'93) was born in Tokyo, Japan, on December 8, 1963. He received the B.E. and M.E. degrees in electrical engineering from Waseda University, Tokyo, in 1986 and 1988, respectively, and the Dr. Eng. degree from Tokyo University, Tokyo.

In 1988, he joined the NTT Transmission Systems Laboratories, Yokosuka, Japan, where he was involved in research and development on high-speed optical communications systems including the 10-Gb/s first terrestrial optical transmission system (FA-10G) using erbium-doped fiber amplifier inline repeaters. He then joined the NTT Electronics Technology Corporation between 1995 and 1997, where he was involved in the planning and product development of high-speed optical module at the data rate of 10 Gb/s and beyond. Since 1997, he has been with the NTT Network Innovation Laboratories, where he has been involved in the research and development of optical transport technologies based on 40- and 100-Gb/s channel. He is currently the Senior Distinguished Researcher and the Director of the Innovative Photonic Network Research Center, NTT Network Innovation Laboratories. His current research interests include high-capacity optical transport systems with advanced modulation formats, digital signal processing, and space-division multiplexing.

He is a Fellow of the Institute of Electronics, Information and Communication Engineers.


**Toshio Morioka** received the B.E. degree in applied physics from Waseda University, Tokyo, Japan, in 1982, the M.S. degree in optical sciences from the Optical Sciences Center, University of Arizona, Tucson, AZ, USA, in 1984, and the M.S. and Ph.D. degrees in physics and applied physics from Waseda University, Tokyo, in 1985 and 1995, respectively.

In 1985, he joined the Yokosuka Electrical Communication Laboratory, NTT Corporation and was a member of the Photonic Transport Network Laboratory, NTT Network Innovation Laboratories, Yokosuka, Japan. He was with the National Institute of Information and Communications Technology, Japan, from 2005 to 2008, working on new generation networks and extremely advanced transmission technologies, which he proposed in order to pursue Pbit/s optical transmission and Exa bit/s networks by developing new transmission fibers and novel multiplexing schemes such as space-division multiplexing and mode-division multiplexing. In 2008, he was the Project Manager at the NTT Network Innovation Laboratories, and has been with the High-Speed Optical Communications Group, DTU Fotonik since October 2011.

He is a Fellow of Optical Society of America and the Institute of Electronics, Information and Communication Engineers, and a member of the Japan Society of Applied Physics, the Laser Society of Japan, and the IEEE Photonics Society/Communications Society.