Advanced Space Division Multiplexing Technologies for Optical Networks [Invited]

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***Abstract*—Space division multiplexing (SDM) is mainly seen as a means to increase data throughput and handle exponential traffic growth in future optical networks. But its role is certainly more diverse. Research on SDM encourages device integration, brings new functionality to network elements, and helps optical networks to evolve. As a result, the number of individual components in future networks will decrease, which in turn will improve overall network reliability and reduce power consumption as well as operational expenditure. After reviewing the state-of-the-art in SDM fiber research and development with a particular focus on weakly coupled single-mode multi-core fibers, we take a look beyond the capabilities of SDM as a means of boosting transmission capacity and discuss ideas and concepts on how to exploit the spatial dimension for improved efficiency and resource sharing in optical networks.**

***Index Terms*—Fiber optics; Optical fiber communication; Optical fiber networks.**

I. Introduction

The worldwide-experienced exponential traffic growth in optical networks of 30% per year and above has been well documented by various statistical studies [1,2], with variations among network segment, geographic region, and application. This growth is fueled by a progressive development of next-generation mobile broadband technologies along with an increasing demand for high-data-rate applications such as streaming video, real-time gaming, social networking services, cloud computing, and big data analysis. Moreover, with the ongoing transition from the current "Internet of Information" to the "Internet of Things," where billions of smart devices will constantly exchange information, machine-to-machine traffic is expected to grow at an even faster pace and may soon outstrip the data traffic generated by humans. Against this backdrop, it is questionable how long current network technologies based on standard single-mode single-core fibers (SMFs) can support such a rapid traffic growth in an economically viable manner. The foreseeable challenges of current communication networks to handle future traffic demands have therefore stimulated serious concerns about a potential capacity crunch in current optical networks [3].

Over the last 30 years, fiber transmission technologies have been constantly refined, and optical engineers have mastered the underlying physics to a point where they can almost fully exploit the available electrical and optical resources in the time domain (in terms of symbol rate), in the frequency domain (in terms of bandwidth), and in the phase domain (in terms of quadrature and multilevel signaling). In this sense, space division multiplexing (SDM) is considered the last frontier to deal with the ever-increasing demand for transmission capacity in optical networks [4]. SDM refers to the multiplexing of orthogonal signals in the space domain and is a generic term for core-division and/or mode-division multiplexing. The usage of the physical dimension "space" for fiber transmission is not a completely new concept and shows up disguised in today's commercial products in simple forms, e.g., as ribbon cables for short-reach interface links containing a linear array of light-carrying fiber cores, or as polarization-division multiplexing (PDM) in coherent optical communication systems where the two orthogonal polarization states of a light wave constitute the two fundamental modes that an SMF can propagate. In fact, PDM represents a very basic form of mode-division multiplexing (MDM) although, most likely for historical reasons, polarization is also sometimes seen as a separate multiplexing dimension [5]. Nonetheless, among all the physical dimensions of an electromagnetic wave, "space" has been so far the one least exploited in optical fiber communications, and finding methods to take better advantage of it has therefore been the focus of interest of researchers more than ever before. As a result, many new ways of using "space" more efficiently have been proposed in recent years, and fiber ribbon/bundle and PDM concepts have been evolving to sophisticated multi-core fiber (MCF) designs [6,7] and few-mode or multi-mode transmission techniques [8,9] dramatically boosting the capacity of a single strand of fiber and clearly demonstrating the potential of SDM.

However, the prospect for more capacity alone seems to have not made these amazing technologies interesting enough yet from a commercial point of view to become quickly and readily accepted as a viable alternative to

Manuscript received October 11, 2016; revised December 27, 2016; accepted December 27, 2016; published February 7, 2017 (Doc. ID 278599).

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https://doi.org/10.1364/JOCN.9.0000C1

Corrected 27 February 2017

the already well-established transmission technologies based on SMFs. To make SDM attractive to network operators, it has to provide significant benefits in terms of cost and energy per bit, ideally in a similar fashion to what the adoption of wavelength-division multiplexing (WDM) has been able to achieve over the last 20 years. In addition, it must also offer a scenario that allows for a smooth transition from today's ceaselessly growing optical networks where fiber cables, once installed in the ground or under sea, are the most difficult and expensive part to replace.

Up to now, SDM related research has been mainly concentrating on increasing the capacity–distance product. Accordingly, SDM is commonly perceived as a technology that boosts capacity by a certain factor. However, we believe that it has a much broader role in the evolution of optical networks. First, research on SDM encourages device integration. Second, it brings new functionality to network elements from which conventional networks will also benefit. Third, it promotes ideas on new transmission and network management methods and thus helps optical networks evolve. With these aspects in mind, we will expand here on the topics presented in [10,11] by first reviewing in detail the main characteristics of SDM fibers, then introducing two examples of MCFs with high core-count recently developed for ultrahigh-capacity point-to-point links, and finally elaborating on advanced applications as well as two possible network scenarios that build on features unique to SDM for enhancing the functionality of optical networks.

II. Characteristics of SDM Fibers

SDM is based on the concept of incorporating multiple independent transmission channels mainly in the space that was hitherto reserved for a single channel. These channels are constructed from fiber cores in the case of an MCF, modes in the case of a few-mode fiber (FMF), or a combination of both in the case of a few-mode multi-core fiber (FM-MCF) [12,13]. The FMF is basically a multi-mode fiber (MMF) that is designed to propagate only a small amount of low-order spatial modes, typically 10 or fewer. Integration of parallel transmitted channels leads to some coupling [or crosstalk (XT)] between channels due to overlapping fields either inside or outside the fiber core, fiber imperfections, and external perturbations such as bending and twists. In general, the coupling between spatial channels in the FMF is stronger than the coupling in MCFs, except for the special case of strongly coupled MCFs [14], where super-modes act similarly to ordinary modes in FMFs [15]. Coupling between spatial channels (i.e., modes) in FMFs can be favorably used to reduce the group delay spread between the modes [16] but increases the complexity of the receiver due to the need for multi-input multi-output (MIMO) digital signal processing (DSP) [17] and also limits options to utilize the spatial dimension for applications other than an increase in the capacity–distance product, since all channels (i.e., modes) have to be received together as one entity to avoid any loss of data. While modes within the same mode group always couple strongly with each other due to very small differences in their effective refractive indices and the presence of unavoidable perturbations in real fibers, the FMF can be designed [18] so that the modes of different mode groups couple only weakly over a limited distance, usually below 100 km. This can be used advantageously to reduce the MIMO DSP complexity as each mode group can be processed separately [19]. On the other hand, in MCFs the amount of coupling or crosstalk is much easier to control by the fiber design, and in most cases the spatial channels in weakly coupled MCFs can be treated independently without resorting to MIMO DSP as long as the total end-to-end XT stays below a certain threshold that depends on the modulation format, e.g., < -23 dB for 16QAM signals for keeping the signal-to-noise ratio (SNR) penalty below 1 dB at a bit error ratio (BER) of 1e–3 [20]. In the remainder of this paper we will therefore focus mainly on the characteristics and applications of weakly coupled MCFs that require no MIMO DSP to compensate for crosstalk.

Crosstalk management in MCFs has been the subject of intense research over the past few years, and various strategies to minimize its impact have been devised. Minimizing the XT stands mainly in tradeoff with maximizing fiber capacity and the mode field diameter to reduce the impact of nonlinear effects, but also affects the cladding size, which, if too large, may weaken the fiber's mechanical reliability (see also Section III.B). Hitherto, the popular trench-assisted core design shown in Fig. 1(a) has proven to be most effective in reducing XT while keeping the fabrication complexity low. As depicted in Fig. 1(b), for this specific core design the field strength at the center location of a neighboring core is reduced by some 20 dB when employing an index trench. From the coupled-mode and coupled-power theories it is well known that an array of homogeneous cores, i.e., cores with exactly the same geometry and refractive index within the same cladding, interchange energy most easily, and in the low XT regime the XT increases linearly with transmission length and fiber bending radius [21].

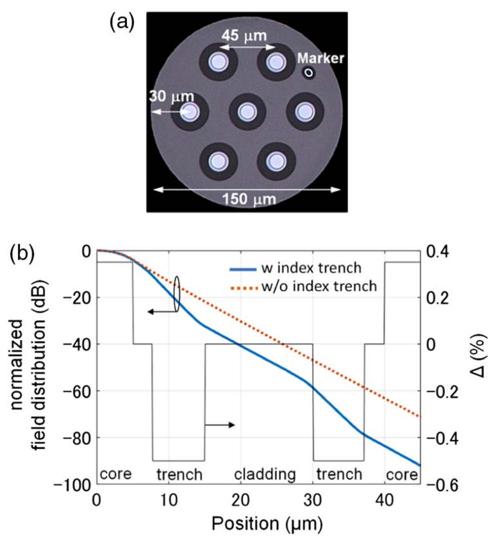

Fig. 1. (a) Cross section of seven-core MCF [23]. (b) Normalized field distribution of the fundamental mode (thick solid and dotted lines) and relative index profile (thin black line).

The dependence on the bending radius has led to investigations of heterogeneous core layouts [22], where each core has a neighboring core exhibiting a slightly different effective refractive index. Although the XT still increases linearly with transmission length, the heterogeneous layout offers the advantage of bend-insensitive and thus generally lower XT above a critical bending radius that can be as small as a few centimeters. However, the heterogeneous layout also complicates the fiber design and manufacturing process for precise control of fiber properties such as cutoff wavelength, mode field diameter, and dispersion parameters with reduced design margins. It may also be less suitable for advanced SDM applications such as those discussed in Section IV due to the larger variations of the optical properties between cores. In fact, the MCF with one of the lowest reported measured XTs (<-90 dB/km at $\lambda = 1550$ nm for a bending radius of 140 mm) and propagation losses (0.18 dB/km) to date is the homogeneous seven-core MCF shown in Fig. 1(a) [23].

Furthermore, we note that even MCFs designed to be homogeneous will in practice exhibit cores with slightly different effective refractive indices, and the XT is likely to peak at some larger bending radius. In this respect, we show in Fig. 2 how the calculated XT characteristics change with bending radius and refractive index difference $\Delta n = 2(n_{c1} - n_{c2})/(n_{c1} + n_{c2}) \approx (n_{c1} - n_{c2})/n_{c1}$ between neighboring cores c1 and c2 when Δn is varied from 0% to 0.05% with the geometric parameters kept as shown in Fig. 1(b). Even for a pair of perfectly homogeneous cores ($\Delta n = 0\%$), the XT will eventually saturate to a constant XT value due to the presence of random structural fluctuations in the longitudinal direction of a real fiber, resulting in a finite correlation length (on the order of several centimeters) of the phase function [24] dictating the maximum amount of energy interchange between the cores. On the other hand, heterogeneous cores typically have an index difference above 0.02%, and the XT curve exhibits a pronounced peak at a relatively small bending radius, known as the critical bending radius, before settling to a bending radius independent low XT value that is mainly determined by the index difference. In general, the XT quickly

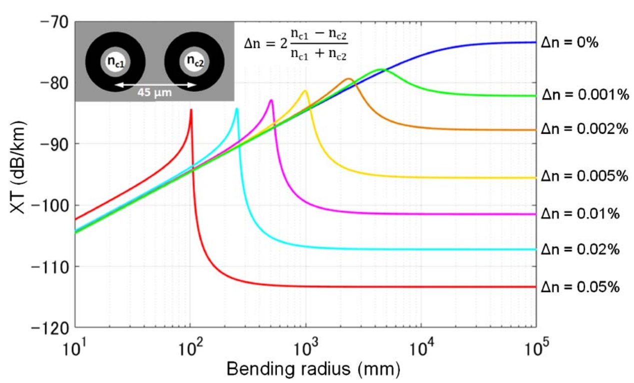

Fig. 2. Calculated average inter-core crosstalk as a function of fiber bending radius in combination with small index variations Δn between neighboring cores when using the index profile shown in Fig. 1(b) and a correlation length of 5 cm. The inset shows the core configuration used for this calculation.

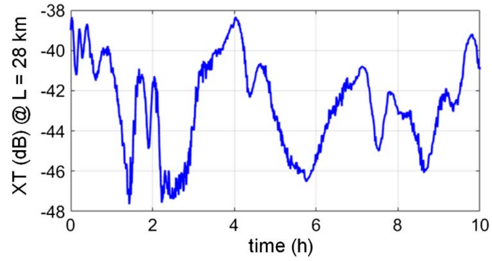

Fig. 3. Measured inter-core crosstalk fluctuations over time in a 28 km seven-core MCF.

increases with decreasing core pitch, making the heterogeneous layout especially attractive for high-core-count MCFs with small core pitches typically around or below 30 µm [6,7].

Theoretical and experimental evaluations have also revealed that the XT in MCFs is a stochastic quantity that may vary over time within a range of up to 10 dB as exemplified in Fig. 3 for the case of a 28 km long seven-core homogeneous MCF, while an average XT for the whole span was calculated to be about −43 dB. These fluctuations have to be taken into account when designing transmission systems and calculating BERs and outage probabilities. Recent investigations showed that these fluctuations result from a complex interference mechanism [25,26] and can impact transmission performance differently than the in-band noise added at a single point, as was previously assumed in simulations [20]. In order to stay below a certain outage probability, the dynamics of the XT will therefore require an XT margin [25,27] that has to be added to the typically reported average XT as depicted in Fig. 4. Outage is defined here as the case in which the temporal XT value is higher than the tolerable maximum XT value to achieve a certain BER. To give an illustrative example, for keeping the XT dependent outage rate below 1 s per day, the required XT margin needs to be around 8.5 dB. Experimental evaluation of transmitting orthogonal frequency division multiplexing (OFDM) signals through a 19-core MCF also showed that the random crosstalk fluctuations lead to a significant degradation of the overall system performance and that transmission schemes that can adapt to fluctuating crosstalk conditions, such as adaptive modulation formats, may be advantageous for exploiting

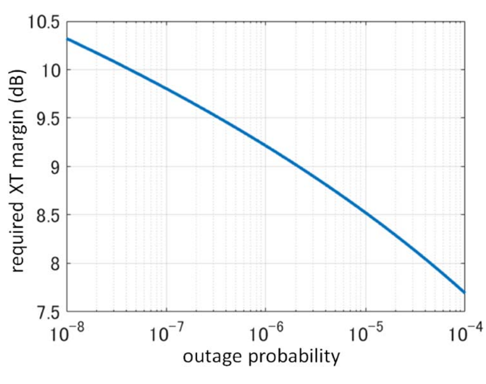

Fig. 4. Required inter-core crosstalk margin for a range of outage probabilities.

MCF systems. These include adapting the modulation format to lower-order QAM and the use of more tolerant coding in the case of single-carrier signals, or the use of dynamic bit-loading with sub-carrier multiplexed signals such as OFDM and discrete multitone transponder (DMT). The latter has already been extensively used in single-core fiber systems to handle dispersion-induced frequency-selective fading [28].

Finally, besides refining the core design itself, the MCF is also well suited to handle bidirectional transmission [29,30], offering the simplest means to dramatically reduce the impact of XT between signals traveling in the same direction.

A second important characteristic of SDM fibers is the amount of differential propagation delay between spatial channels, which in the case of MCFs is referred to as the inter-core skew. Advanced SDM applications, such as those discussed in Section IV, exploit the correlation between spatial channels, and thus the skew should remain within a certain manageable range if full exploitation of the spatial dimension is desired. The inter-core skew consists of (a) a systematic skew caused by the fiber fabrication process as well as the method of fiber storing, such as spooling, and (b) a stochastic skew (SSK) introduced by environmental perturbations such as temperature fluctuations and mechanical vibrations. For advanced SDM applications, the amount of SSK will have an impact on achievable baudrates, transmission distances, and receiver design including the complexity of the DSP. A thorough characterization of the SSK over extended periods of time is therefore crucial to assess the usefulness and applicability of advanced SDM applications. As shown in Fig. 5(a), we measured the SSK of a 28 km long seven-core MCF and compared it with that

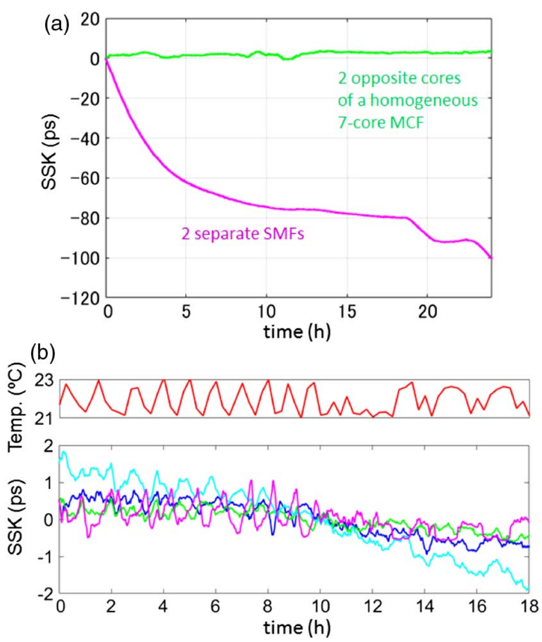

Fig. 5. (a) Comparison of stochastic skew (SSK) between a pair of MCF cores and a pair of thermally insulated SMFs. (b) Enlarged view of the SSK of several MCF cores together with the temperature fluctuations over time.

of a pair of 25 km long single-mode fibers (SMFs) that were thermally insulated to emulate a fiber bundle [31].

The SSK in the fiber pair was more than an order of magnitude larger than the one in the MCF over a 24 h period, demonstrating that the cores in an MCF experience much stronger correlated environmental perturbations and the MCF is thus capable of maintaining lower SSK fluctuations over an extended time period. Further investigations on the SSK of all six outer cores relative to the center core of the MCF in combination with a precise ambient temperature measurement around the spooled MCF revealed that even small temperature fluctuations on the order of ±1°C can already have an influence on the SSK, as illustrated in Fig. 5(b). Despite sensitivity to such environmental perturbations caused by lab activity, the maximum skew variations nevertheless always stayed below 4 ps for all cores measured over an 18 h period, which we believe is an encouraging result for applications aiming at the full exploitation of the spatial dimension.

III. High-Core-Count MCFs

Before moving on to the discussion of advanced applications for SDM fibers, in this section we briefly revisit some achievements obtained with MCFs in terms of maximum transmission capacities and maximum spatial channel count. The first successful demonstration of transmitting data rates exceeding 100 Tb/s in 2011 [32] using the seven-core MCF shown in Fig. 1(a) triggered an intense competition of developing MCFs with a higher spatial channel count. In early 2012 a 19-core MCF carrying 305 Tb/s was reported [33], and by the end of 2012 two groups had already independently demonstrated transmission capacities exceeding 1 Pb/s. One group used a 52 km 12-core homogeneous MCF carrying in each core 222 channel WDM signals with PDM and 32QAM (quadrature amplitude modulation) single-carrier frequency division multiplexing [34], and the other group used a 3 km 14-core heterogeneous MCF that employed a combination of 12 single-mode cores carrying PDM-32QAM-OFDM signals and two three-mode cores carrying PDM-QPSK (quadrature phase-shift keying) signals in each mode [35]. In 2015, the capacity record was doubled to 2 Pb/s, again in two independent transmission experiments. One used a 31.4 km 22-core single-mode MCF in combination with a wideband optical frequency comb source [36], and the other used a 9.8 km 19-core six-mode MCF where each mode carried 360 C-band wavelength channels spaced at 12.5 GHz with each channel carrying 50 Gb/s PDM-QPSK signals [37]. In the following, we discuss in more detail two types of high-core-count MCFs, the homogeneous single-mode MCF and the heterogeneous FM-MCF, that we believe are good candidates for bringing out the ultimate potential of SDM.

A. Homogeneous Single-Mode MCF

As a representative for this type of MCF, Fig. 6(a) depicts the cross section of our homogeneous 22-core MCF that was

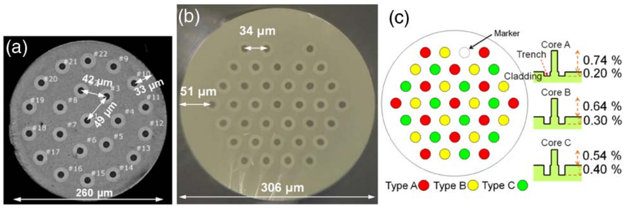

Fig. 6. (a) Cross section of 22-core single-mode MCF. (b) Cross section of 36-core three-mode MCF. (c) Core layout and core index profiles of 36-core MCF.

developed for multi Pb/s long-haul transmission [36]. It has a cladding diameter of 260 μm and employed a three-layer core design with two rings of seven and 14 cores circularly arranged around the center core. A two-pitch layout with average intra- and inter-ring core pitches of 42 and 49 μm in combination with index trenches kept the maximum aggregate XT below −45 dB/km over the whole transmission span of 31.4 km. The core in the top center (#22) was designed with a slightly wider trench to serve simultaneously as a marker. The whole span was spliced from five separately drawn sub-spans. Although the average fiber loss for each sub-span stayed under 0.21 dB/km, the total insertion loss (including coupler losses) ranged from 8.4 dB for the center core to 13.3 dB for the worst outer core due to alignment errors and core pitch variations between individual sub-spans, pointing out the need for more precise control of the core pitch when the MCFs originate from different preforms. Table I summarizes the main optical transmission properties for each core group. Crucial to achieving Pb-class transmission rates was the decision of combining the 22-core MCF with a novel wideband narrow-linewidth optical frequency comb source [38] consisting of a 5 kHz narrow-linewidth seed laser modulated with a low-noise 25 GHz oscillator. The resulting 25 GHz spaced comb was spectrally broadened in a dispersion-engineered fiber mixer based on a highly nonlinear fiber providing some 400 lines covering a total bandwidth of 10 THz from 1510 to 1620 nm. Each MCF core was fed with a set of decorrelated comb lines acting as WDM signals carrying 64QAM modulation at 24.5 Gbaud, which eventually resulted in the successful transmission of 2.15 Pb/s.

B. Heterogeneous Few-Mode MCF

No upper limit has yet been defined for the maximum number of cores that can be practically packed into a single

TABLE I
Optical Properties of 22-Core MCF Measured at $\lambda = 1550$ nm

	Center Core	Inner Core Average	Outer Core Average
Fiber loss (dB/km)	0.19	0.20	0.21
Splice loss (dB)	0.1	0.4	1
MUX or DEMUX loss (dB)	0.95	0.85	0.95
A_{eff} (μm^2)	75	76	75
Cutoff λ_{cc}(μm)	<1.48	<1.47	<1.45

strand of MCF. However, it is evident that this number will eventually be limited by the tolerable XT and cladding diameter, which in turn affects the fiber's mechanical strength. Cladding diameters up to 250 μm are currently considered to be able to maintain a silica fiber's long-term mechanical reliability at a level that is comparable to the one used in current SMF networks [39], and it was recently shown that by adopting a heterogeneous core layout, 32 cores can be embedded within such a cladding diameter while keeping the XT still below −60 dB/km [7]. Furthermore, we note that with the ongoing development of low-loss high-bandwidth plastic fibers [40], the constraint imposed on the fiber diameter may become less relevant in the future. Especially with respect to access, intra-building, and intra-datacenter networks, or in general short-reach links up to 1 km that can tolerate loss levels of a few dB/km and where the exploitation of the spatial dimension can be very cost effective among various multiplexing technologies (see also the application to filterless networks introduced in Section V), we could envision the use of plastic super-MCFs with cladding diameters much larger than 250 μm embedding 100 cores or more.

On the other hand, an MMF can propagate over hundreds of spatial modes without any need to enlarge the cladding size. Each mode constitutes an independent spatial channel, provided that the information on each channel can be properly retrieved at the receiver. However, the complexity of the required MIMO DSP dramatically increases with the number of modes and thus quickly increases implementation cost and adds practical limitations. To obtain SDM fibers with the highest spatial channel count, a logical choice is to merge the core- and mode-division technologies. As such, the number of reports on successful transmission experiments based on FM-MCF has been growing over recent years. So far, these impressive demonstrations have already brought forth MCFs with more than 100 spatial channels while supporting up to six spatial modes per core [37,39].

In terms of heterogeneous FM-MCF, we also developed a 36-core 3-mode MCF and demonstrated successful transmission with 108 spatial channels over 5.5 km [41]. Figures 6(b) and 6(c) depict the MCF's cross section, index profiles, and core distributions. A heterogeneous core layout using three different types of cores was employed with the refractive indices differing from core type to core type by 0.1%. The main parameters for each core type are summarized in Table II.

The 36 cores were embedded in a cladding with a diameter of 306 μm and arranged on a four-layer hexagonal lattice with a core pitch of 34 μm resulting in a maximum average XT for the LP_{11} modes of about −38 dB/km. One core in the outmost layer was omitted to serve as a marker. The transmission characteristics were evaluated by launching 40 PDM-QPSK modulated wavelength channels into each mode for the core under test and 105 dummy SDM channels, respectively. Nine wavelengths distributed throughout the 40 wavelengths were selected as test channels for the BER measurement with the remainder used as dummy channels. On the receiver side, 6×6 MIMO

TABLE II
OPTICAL PROPERTIES OF 36-CORE MCF MEASURED AT $\lambda = 1550$ nm

Core Type	Type A	Type B	Type C
Fiber loss (dB/km)	0.26	0.29	0.3
A_{eff} (μm^2)LP$_{01}$/LP$_{11}$	77/105	74/102	76/110
Cutoff λ_{cc}(μm)	<1.53	<1.36	<1.25
DMD (ps/m)	7.4	7.1	6.3
XT (dB) @ 5.5 km for LP$_{11}$	–54	–31	–32

equalization was performed for demodulation. To cope with the relatively large total DMD of about 40 ns due to the step-index core profile, we used a sparse MIMO technique [42] to reduce the calculation complexity and achieved for all spatial modes BERs below 3.5e–3, which was assumed as the threshold for forward error correction (FEC) with 7% coding overhead. As one of the first FM-MCFs with more than 100 spatial channels, the cladding diameter considerably exceeded the currently considered limit for long-term mechanical reliability of silica MCFs; however, it was recently shown that a more optimized core-to-mode of ratio of 19:6 can achieve a similar amount of spatial channels while keeping the cladding diameter below that limit [39].

IV. ADVANCED SDM APPLICATIONS AND NETWORK ENHANCEMENTS

Given the ongoing research on crosstalk and skew, it is likely that adequate SDM fibers will become available in the future that keep these impairments at a negligible or manageable level. Such fibers will then open up new possibilities for advanced SDM applications that more efficiently share both physical and DSP resources between channels and thus improve the flexibility and efficiency of short- to medium-haul optical fiber transmission. One such application may be the spatial superchannel (SSC). In general, superchannels refer to the grouping of M signals that provide M times more instantaneous bandwidth in a single operation cycle with M being an integer. Originally devised for the wavelength domain, the superchannel concept has led to a rethinking of spectral bandwidth allocation beyond the current fixed grid architectures leading to a flexible grid architecture that allows a more efficient utilization of the optical spectrum. The same concept can be applied to the spatial domain. An SSC is formed by grouping together signals in different cores operating at the same wavelength and thus can provide a very large instantaneous bandwidth. SSCs were first proposed for sharing hardware and DSP resources that are common to all cores of an MCF [43]. But this concept can also be extended to new spatial modulation formats that enable greater design flexibility by increasing the number of dimensions over which the optical modulation is applied [44]. An SSC does not necessarily need to simultaneously occupy all cores of the MCF, but could constitute a subset of cores referred to as a "superchannel slice" as shown in Fig. 7, thereby increasing switching granularity in a network. In this case, the core number, i.e., bandwidth assigned to each superchannel slice, can be flexibly adjusted according to traffic demands. Finally, we note that the SSC concept can be equally applied to FMFs/MMFs in conjunction with some MIMO DSP. Nevertheless, we think that homogeneous MCFs with their inherently very small differential group delays between spatial channels currently offer the most simple and flexible option for studying SSC transmission.

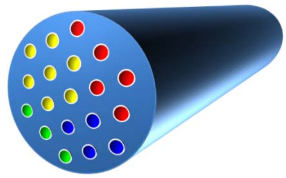

Fig. 7. Example of four sliced spatial superchannels.

Another advanced application of SDM that promises savings in hardware and DSP resources is self-homodyne detection (SHD) [45–47]. In SHD, a transmitted pilot-tone (PT) originating from the transmitter laser is space-multiplexed in the MCF with the data signal and used as a local oscillator for coherent reception, as shown in Fig. 8. Besides making the local oscillator (LO) laser at the receiver side dispensable, the usage of a PT originating from the same optical source as the data signal reduces the impact of laser phase noise in the detection process and thus encourages the use of spectrally efficient high-order modulation formats with relaxed requirements on narrow-linewidth laser sources, such as DFB lasers with linewidths of several megahertz or more. However, such advantages are not for free. The reduction in spectral efficiency due to the PT transmission compared to an equivalent intradyne (ID) scheme is inversely proportional to the number of spatial channels, e.g., 5.3% SE reduction in the case of a 19-core MCF, and the accumulation of noise on the PT during transmission results in a slight degradation of the optical-to-signal noise ratio (OSNR). For typical system configurations, this OSNR penalty ranges from about 1 to 2 dB and is largely determined by the bandwidth of the optical filter used to limit the PT noise bandwidth at the receiver and the ratio between the OSNR of the signal and the PT [48].

The prospect of employing SHD in MMF systems was investigated numerically [49] and implemented for an access

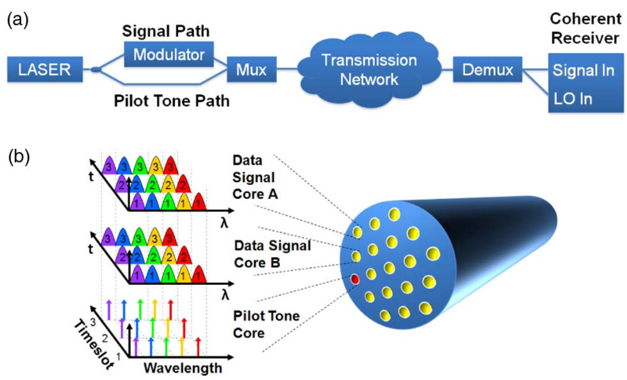

Fig. 8. (a) Schematics of a self-homodyne transmission system. (b) Signal distribution in data-signal cores and the pilot-tone core.

network scenario in [50]. Yet, the majority of experimental demonstrations of SHD in SDM systems have used MCFs due to the relative ease of aligning the path length between cores. Initially, we investigated the feasibility of SHD for linewidth sensitive 5 Gbaud QPSK signals [51], before we moved on to a high-capacity transmission experiment over a 10.1 km 19-core MCF in combination with a low-cost DFB laser exhibiting a linewidth of 2.9 MHz. In this experiment, we demonstrated a 105 Tb/s transmission using 25 GBd QPSK signals on 125 wavelengths with 50 GHz channel spacing. Next, we upgraded to a 210 Tb/s WDM–SDM–PDM transmission with the use of PDM-QPSK signals. This transmission rate, assuming a 7% overhead for FEC, resulted in an SE of 33.4 b/s/Hz [52]. More recently, long-distance SHD transmission was investigated using a setup with parallel recirculating transmission loops, where self-homodyne transmission over 6800 km was observed for a BER of 1.5e–2. Compared to transmitted signals received with an ID receiver, we found that the difference in distances was consistent with the measured back-to-back penalty of 1 dB [53].

Finally, a third network enhancement instituted by SDM could be wavelength contention management solely done in the optical domain. In current networks, different traffic demands with the same wavelength cannot be routed through the same link due to wavelength contention. To solve this problem without having to resort to optical–electrical–optical (OEO) conversion, much hope has been placed in research on all-optical wavelength converters based on semiconductor or periodically poled lithium niobate devices and highly nonlinear fibers. However, the trend towards using digital coherent transmission techniques in future optical networks may substantially limit the range of potential solutions. This in turn will also make it increasingly challenging to convert those research outcomes into efficient and practical products due to the intrinsic properties of the optical processes involved [54]. Therefore, it is likely that networks based on SMF will continue to rely on routing and wavelength assignment (RWA) algorithms and OEO regeneration to minimize the probability of blocking due to wavelength contention. On the other hand, in an SDM network based on MCFs the wavelength contention problem could be mitigated solely in the optical domain, since core (i.e., spatial channel) switching can be easily incorporated in the node. For instance, if there is an add request with a high quality-of-transport (QoT) requirement against a less impaired but already occupied channel (core), the express traffic with less stringent QoT requirements can be temporarily switched to another (by the same wavelength) unoccupied spatial channel with less favorable transmission characteristics. The risk of having to block a new request can thus be effectively averted in the optical domain.

V. Toward the Realization of SDM Networks

While there have been only two types of fibers (SMF and MMF) available for designing conventional networks, the variety of fibers that emerge from today's SDM research is likely to be reflected in future networks where different types of fiber will serve better individual needs of different network segments. The introduction of SDM into the network will increase capacity and switching flexibility but also add new challenges to an already complex network control.

In collaboration with the University of Bristol, we demonstrated how the network architecture based on architecture on demand (AoD) nodes in combination with an appropriate software defined networking (SDN) control can exploit SDM features to add flexibility to a network. An AoD node consists of an optical backplane implemented by, e.g., a large port-count 3D-MEMS switch, to which several pluggable modules are connected providing a set of signal processing functions, such as optical amplification, spectrum/wavelength/sub-wavelength switching, wavelength conversion, and signal regeneration. For the experiment, we used three AoD nodes, linked by SMFs and two MCFs with 19 and 7 cores, respectively [55]. SDN provided four key features that make it suitable for such heterogeneous networks. First, the data and control plane are separated, which allows an independent evolution of the network and control software as well as network virtualization where the SDM infrastructure can be partitioned (sliced) into multiple logically isolated units. Second, the network control is centralized, which leads to a better overview and stability of the network. Third, open, i.e., vendor-independent, interfaces are used between the software/hardware in the control and data planes, which achieves plug-and-play operation of the network. Fourth, programmability of the network by external applications due to the abstraction of the underlying network infrastructure by the SDN controller enables fast development of new services and a rapid evolution of the network. As shown in Fig. 9, communication between the control and data plane is carried out with an OpenFlow [56] interface at the control plane side and OpenFlow agents at the data plane side. The MCFs were abstracted as a single entity with multiple spatial channels whose information is used by the slicing service for routing SSCs. Signals on different spatial channels but operating at the same wavelength were grouped into SSC slices to provide more

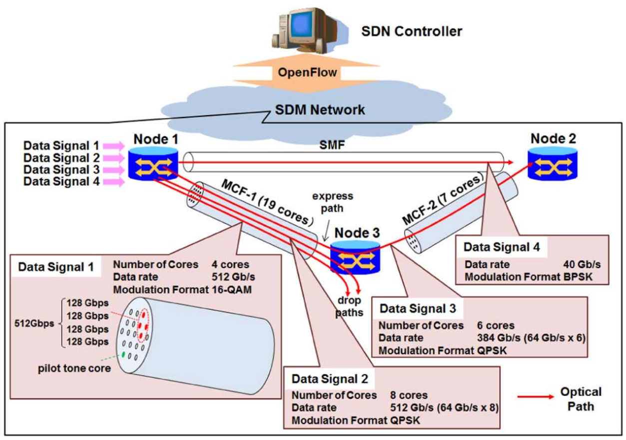

Fig. 9. Schematics of an SDN controlled SDM network utilizing sliceable self-homodyne spatial superchannels.

instantaneous bandwidth to a single request. For example, a 19-core MCF could be abstracted as three SSC slices consisting of four, six, and eight cores carrying 512, 768, and 1024 Gb/s, respectively, while each core by itself carries only 128 Gb/s (per wavelength). On the other hand, the SMFs were abstracted as multiple entities each with a single independent spatial channel and therefore were not suitable for transmitting SSCs. An example of data flow using these different types of spatial channels is also illustrated in Fig. 9. The SDN controller translates connectivity requirements such as source, destination, and QoT into physical layer requirements such as the number of cores, wavelength, data rate, and modulation format. Each data signal is then assigned to either a single SMF core or a group of MCF cores representing a superchannel slice. In this way, flexible bandwidth provisioning from 40 to 512 Gbps together with different QoT requirements could be demonstrated.

In recent years it has been recognized that in order to increase the data throughput efficiency networks need to be flexible and elastic, i.e., provide some means that let the network dynamically adapt to unpredictable traffic patterns and rapidly establish or tear down connections. Typically, this is performed using reconfigurable optical add/drop multiplexers (ROADMs) that are based on multiple stages of wavelength selective switches (WSSs). However, repeated signal filtering degrades the signal quality with wavelength switching leading to increased cost and power consumption compared to passive networks [57]. Also, since entire links must be reconfigured to add capacity, the complexity of routing algorithms increases. Passive networks without switching avoid these problems by using only splitters or couplers and fiber trees, but as signals are broadcast on all links, light paths cannot be reused and the lack of filtering also leads to security issues since channels are present in unintended receiver ports. To address this issue, we carried out a second network experiment [58] based on SDM fibers and the AoD concept to eliminate passive optical components and spectrum filtering devices, whilst being able to offer robust privacy and confidentiality through dedicated spatial channels, which is not possible in broadcast-and-select access networks. The scheme also allows hitless dynamic bandwidth allocation without the need for network reconfiguration and thus simplifies the switching architecture as well as eliminates drop-and-waste. The absence of filters improves the efficiency in terms of energy and cost as well as increased signal integrity and transmission distances. We investigated this concept with an emulated seven-node network connected by four different types of MCFs as shown in Fig. 10(a) with several advanced modulation formats from QPSK to 64QAM that resulted in a switching granularity ranging from 100 Gb/s to 3.3 Tb/s. Various scenarios including bidirectional transmission, multicasting, and filterless multihop long-distance transmission showed good suitability for future inter-datacenter and metro networks. The experimental setup shown in Fig. 10(b) mainly consisted of an optical frequency comb as transmitter, a MEMS switch, four different MCF spans, and a coherent receiver. The comb source provided 25 GHz spaced

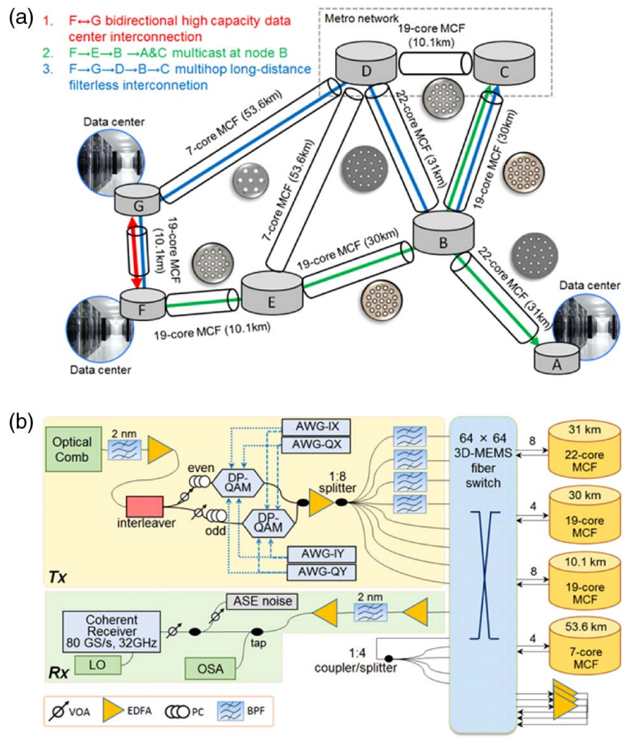

Fig. 10. (a) Investigated network architecture of a filterless SDM network including three examples for transmission scenarios. (b) Experimental setup of the filterless SDM network.

wavelength channels whose even and odd contributories were interleaved and modulated using two high-bandwidth DP-QAM modulators driven by four arbitrary waveform generators (AWGs) to generate QAM modulated signals at 24.5 Gbaud. After recombination, the modulated signals were split into eight copies. Four copies went through filters to demonstrate different frequency slot combinations, whereas the rest were used as background traffic. The 64 × 64-port optical MEMS switch represented the optical backplane to which, besides the MCFs, couplers and EDFAs were also connected. Due to the limited amount of switch input ports, only subgroups of four to eight cores from each MCF were used. Ten different inter-connection scenarios varying in length and node number were tested with the three modulation formats DP-QPSK, DP-16QAM, and DP-64QAM and measured the OSNR penalties. The results showed a much lower dependence of penalty increase on the number of nodes than the one expected in an equivalent WSS-based scenario due to the unavoidable passband narrowing effect of cascaded WSSs [59].

VI. Outlook and Conclusion

In the short term, the capability of handling higher capacities will not immediately make SDM a game changer in the telecom industry, and the required physical layer capacity will most likely be provisioned by deploying more SMFs per link and deriving more flexibility from the underlying network technology. However, as network evolution strongly depends on reducing cost (and energy) per bit, it is also clear that one cannot rely on SMF networks forever, and it may not take too long before a tipping point is reached where SMF networks based on massive fiber bundles and separate network elements are no longer economically viable [60]. Although the timing for this tipping point depends strongly on the individual application, we envisage that SDM technology will be adopted first in short-reach links for datacenter applications to minimize cable density as well as interface costs [61] and in long-haul links of submarine systems to increase energy efficiency [62]. Yet, whatever application or network segment SDM technology will be applied to, its development and the associated trend towards greater device integration are always a consequence of the continuing quest for more efficient optical networks, and in order to succeed SDM research has to continuously address the efficiency issues of current networks.

Both MCF and FMF/MMF technologies show tremendous potential to keep up with the network capacity scaling needs of future generations. We believe that most constraints currently associated with either technology will be relaxed by further research progress. For example, the problem related to the mechanical reliability of silica MCFs with cladding diameters beyond 250 μm may be mitigated by improved buffers surrounding the cladding or replacing silica with other materials such as low-loss plastic. Moreover, MCFs possessing the same cladding diameter and fulfilling the same ITU standards as SMFs but including up to five cores with an XT below −60 dB/km have also been investigated [63] to provide a smooth upgrade path from single-core single-mode networks to SDM networks. Similarly, the MIMO processing complexity in receivers of FMF/MMF systems may be mitigated by more efficient and faster application-specific integrated circuits, and by dividing the modes into mode groups that can be processed independently.

In this paper we mainly discussed MCFs and associated transmission and network scenarios since their characteristics make them currently the most attractive candidates for studying advanced SDM applications that explore the last available multiplexing dimension in optical communications beyond simply multiplying the achievable transmission capacity.

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