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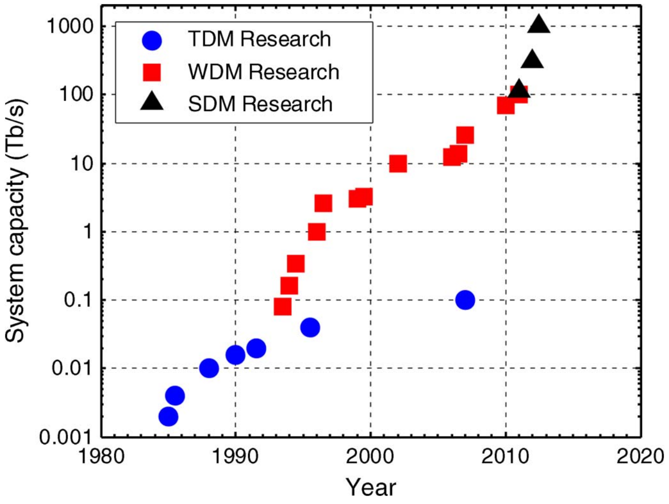
R.-J. Essiambre, Fellow, IEEE
R. Ryf, Member, IEEE
N. K. Fontaine, Member, IEEE
S. Randel, Senior Member, IEEE



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Breakthroughs in Photonics 2012: Space-Division Multiplexing in Multimode and Multicore Fibers for High-Capacity Optical Communication

R.-J. Essiambre, ***Fellow, IEEE*****, R. Ryf,** ***Member, IEEE*****,**
N. K. Fontaine, ***Member, IEEE*****, and S. Randel,** ***Senior Member, IEEE***

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Bell Laboratories, Alcatel-Lucent, Holmdel, NJ 07733 USA

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Manuscript received February 15, 2013; accepted March 5, 2013. Date of publication April 25, 2013; date of current version May 2, 2013. Corresponding author: R.-J. Essiambre (e-mail: rene.essiambre@alcatel-lucent.com).

Abstract: We summarize the latest advances in space-division multiplexing (SDM) for increasing the capacity per fiber strand. We discuss SDM fibers, recent SDM transmission experiments, subsystems suitable for SDM systems, as well as integrated components able to manipulate multiple spatial modes within a single optical device.

Index Terms: Multimode fibers (MMFs), multicore fibers (MCFs), space-division multiplexing (SDM), information theory, optical amplifiers, optical couplers, mode coupling, waveguides.

The development of systems using space-division multiplexing (SDM) in fibers [1]–[7] appears as a promising technological path to increase the capacity of optical networks through an increase in the capacity per fiber strand (see [8]–[10] for recent proposals and [11]–[13] for recent reviews). A strong impetus behind working toward SDM in fibers is the fast approaching capacity limit of single-mode fibers (SMFs) due mainly to the Kerr fiber nonlinearity [14], [15]. Closely approaching this limit requires advanced technologies such as arbitrary waveform generation at the transmitter and coherent detection at the receiver, both making use of digital signal processing (DSP), near-capacity-achieving forward-error correction, distributed optical amplification, and quasi-rectangular optical add–drop multiplexer (OADM) filters. The capacity limit for a 500-km link using polarization-division-multiplexed signals over standard SMF in an optically routed networks is ~17 bits/s/Hz. For an 80-nm (C+L)-band optical amplifier, the estimated capacity is 170 Tbits/s, while the current capacity record for wavelength-division multiplexing (WDM) over SMF is ~100 Tbits/s (see Fig. 1). Future improvements in SMFs, such as a dramatic reduction in loss or nonlinear coefficients, are expected to increase fiber capacity but by no more than a factor of two [15]. As a result, utilizing fibers supporting multiple spatial modes is foreseen as the most efficient way to increase capacity per fiber, as the capacity scales with the number of modes in the absence of mode-dependent loss (MDL) or mode-dependent gain (MDG) [3], [16], [17] or nonlinear effects between modes [15].

1. SDM Fibers and Systems

Fig. 1 displays record capacities achieved over a single strand of fiber in laboratory settings over the last three decades sorted by the latest technology used to increase capacity: time-division

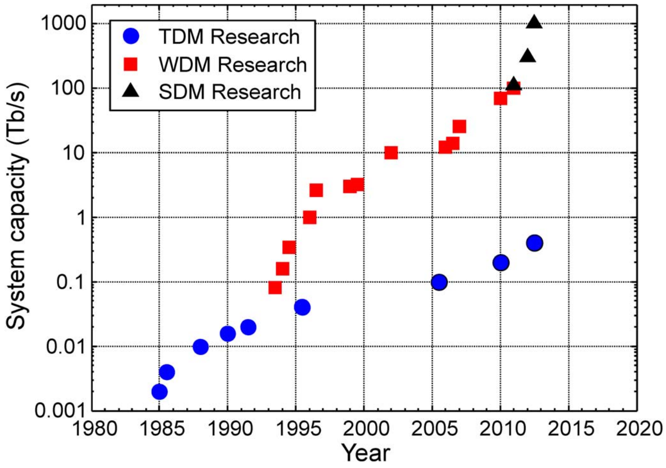

Fig. 1. Capacity evolution over the last three decades. High-capacity SDM systems demonstrations started in 2011.

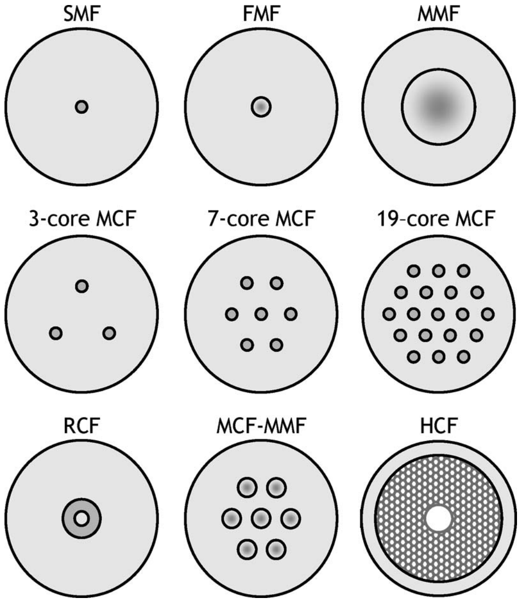

Fig. 2. Cross section of various optical fibers. Darker areas represent regions of higher refractive index. Black lines are used as delimiters.

multiplexing (TDM), WDM, and SDM. TDM systems required mainly improvements in electronic speeds and optical transmitters and receivers, while WDM systems required broadband optical amplifiers and optical components. Emerging SDM systems require development of fibers that support multiple spatial modes, optical amplifiers that can operate on a large number of modes with a reduced number of optical components, spatial mode multiplexers (SMUXs) and demultiplexers (SDEMUXs), and OADMs compatible with SDM. A variety of SDM fibers can be envisioned that enable spatial multiplexing as shown in Fig. 2. Current communication fibers are SMFs. All the other fibers displayed in Fig. 2 can, in principle, support more than one transverse mode: few-mode fibers (FMFs), multimode fibers (MMFs), multicore fibers (MCFs) with a diverse number of cores, ring-core fibers (RCFs), hybrid MCF-MMFs, and a special type of photonic crystal fiber, i.e., the hollow-core fiber (HCF).

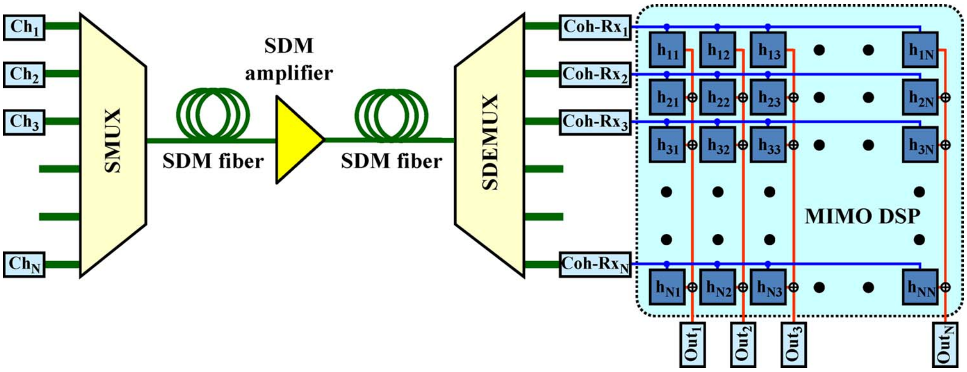

Fig. 3. Schematic of a SDM transmission system based on coherent MIMO DSP. A single WDM channel transmitting over N fiber modes is represented for simplicity.

From the point of view of transmission, one can distinguish between two categories of SDM fibers. The first category targets near total suppression of coupling between modes so as to minimize crosstalk. We refer to such SDM fibers as uncoupled-mode fibers (UMFs). A second category allows linear coupling between modes and accumulation of large crosstalk. This category of SDM fibers requires using multiple-input multiple-output (MIMO) DSP on the output fields recovered by an array of coherent receivers (Coh-Rxs) [4], [18], [19]. We refer to this second category of SDM fibers as coupled-mode fibers (CMFs). One type of UMF is the MCFs with a core separation sufficiently large so as to reduce linear coupling between cores [20], [21]. The requirement of low crosstalk generated by linear coupling in UMFs limits the spatial density of cores in MCFs. Alternatively, one can use heterogeneous cores that reduce crosstalk [22]. For uncoupled-mode MMFs, one can design such fibers with sufficiently different propagation constants between most spatial modes so as to suppress linear coupling under ideal conditions [23]. For both types of UMFs, the main challenge is to fabricate fibers that have a large spatial density of modes while preventing spurious linear mode coupling induced by fabrication or environmental conditions. In the case of CMFs, linear coupling is permitted that allows a larger density of cores in MCFs. For coupled-mode MMFs, there is no need to suppress linear mode coupling by design and additional linear coupling generated by fiber imperfections and many forms of mechanical stress can be largely recovered using MIMO-DSP technology. In general, any unitary transformation can be undone by MIMO-DSP, virtually penalty-free, as long as the equalizer memory is sufficient [16], [18].

We now discuss recent experiments using SDM transmission. A typical experimental setup for N-mode SDM transmission is shown in Fig. 3. The number N of modes is counted by the number of *true* modes in a fiber. It corresponds to $N/2$ linearly polarized (LP) modes [24] in the weakly guiding approximation, also referred to as *spatial* modes. Transmission over CMFs with large crosstalk have been recently reported in a coupled-core three-core MCF [25], as well as in FMFs supporting three spatial modes [26] and six spatial modes [27]. The coupled-core three-core MCF consisted of three single-mode cores with large effective areas of 129 μm^2 and with a core-to-core spacing of 29 μm. Even if the cores are physically separated, the fiber shows complete linear coupling between cores even after only a few meters of fiber due to the proximity of the cores and their large effective areas. In a 60-km-long span, arranged in a recirculating loop configuration, a transmission distance of 4200 km has been demonstrated. A similar transmission experiment was reported using an FMF supporting three spatial modes (LP01, LP11a, and LP11b) with a maximum transmission distance of 1200 km. The fiber was based on a graded index profile, which was optimized to support exactly three spatial modes, and also to reduce the differential group delay (DGD) between modes. Reducing the DGD is necessary to reduce the memory depth requirements for MIMO-DSP.

In order to reduce the impact of the residual DGD present in the fiber, DGD compensation consisting in alternating fiber segments with DGD of opposite signs has also been investigated [28]. Transmission in graded-index MMF supporting six spatial modes (namely, LP01, LP11a, LP11b, LP21a, LP21b, and LP02) has recently been demonstrated for a transmission distance of 130 km

[27]. The transmission distance was limited by the DGDs of the fiber, and in particular, for an MMF supporting six spatial modes, multiple DGDs between all modes have to be matched at the same time. A critical component that enables transmission over FMFs with a large number of modes is the "photonic lantern" described in the next section.

SDM systems based on UMFs are also of great interest and typically consist of MCFs [6], [7], [29] or FMFs optimized to reduce crosstalk between the nondegenerated modes [30]. Early transmissions over MCFs [6], [7], [29] were based on a seven-core MCF design. The spacing between the cores was around 45 μm, and a fiber cladding diameter around 190 μm, considerably larger than the 125 μm of a typical SMF. More recently, fibers were designed to investigate ways to reduce the crosstalk between the cores, for example, by using heterogeneous core arrangements or using "barriers" around the cores and other designs that further increase the number of cores. The highest capacities per fiber of 1 Pb/s have been demonstrated using uncoupled-core MCFs [31] due to the difficulties to perform MIMO-DSP at such high capacities in CMFs.

A complete SDM system requires SDM optical amplifiers and SDM wavelength selective switches (WSSs). In FMFs, distributed Raman amplification has been demonstrated, and the issue of preferential amplification of the fundamental LP01 mode, resulting in a large MDG that is detrimental to SDM transmission performance, has been addressed by selective mode excitation of the Raman pump. SDM erbium-doped optical amplifiers (EDFAs) for FMFs [32]–[34] have also been demonstrated, and the MDG variations have been minimized by using an optimized doping profile of the erbium dopant. Optical amplification has further been studied in MCFs; in particular, it has been shown that MCFs with erbium-doped cores can amplify multiple spatially separated channels, either by individually pumping the cores [35] or by pumping the cladding [36], and thus sharing a single pump over all cores. Even if these first demonstrations are compelling, advances on integration of optical components are required to extract the full benefit of SDM amplification. Demonstrations of SDM WSSs are still in early stages, but first proof-of-principle demonstrations [37], [38] look promising.

2. Components and Devices

Compared with SMF systems, SDM systems introduce several additional challenges and opportunities for integrated devices: building compact and low-loss SMUXs and SDEMUXs to couple to different spatial modes, unscrambling the crosstalk between modes all-optically, and building components to be used in SDM amplifiers and SDM WSSs. The main opportunity is to create SDM free-space components and integrated devices that simultaneously process all N modes with the same component count as a single-mode device. This has the potential for providing significant cost savings over assemblies of single-mode devices.

Ideally, SMUXs should interface all N SDM modes of an SDM fiber to exactly the $N/2$ (LP01) modes of an SMF or to N SDM modes of another SDM fiber. A necessary condition for the broad use of SDM devices is to obtain a level of performance similar to single-mode devices. This means that, in addition to the low wavelength and polarization dependence of single-mode devices, a low dependence on the spatial mode for all N modes is necessary. More specifically, it is important to achieve a low MDL, a device property that can reduce system capacity [16], [17]. In the case of SDM systems using CMFs with MIMO-DSP, optical components and devices are allowed to perform unitary scrambling of the modes without incurring additional penalties.

Mathematically, the SMUX can be described as an $N \times N$ matrix relating the inputs to the outputs similar to the MIMO matrix shown in Fig. 3. The most common type of SMUX maps single-mode inputs onto each of the fiber modes by creating free-space beams with the same field patterns using either phase masks or computer generated holograms [39]. These can achieve low MDL since all the modes can be excited equally. The drawback is that insertion loss (IL) scales with the number of modes as $1/N$ due to splitting loss ratios. Spot-based couplers or spatial-beam samplers excite different spatial locations of the fiber with spatially separated spots [40], [41]. Selecting an optimal spot arrangement ensures that each spot maps to a near-orthogonal combination of modes. These spot multiplexers can support a large number of modes without increasing IL.

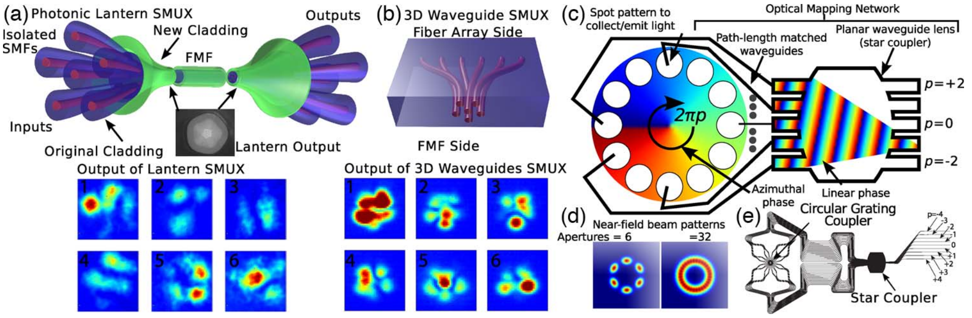

Fig. 4. (a) Vanishing core and (b) 3-D laser-inscribed waveguide photonic-lantern SMUXs. (c) Orbital angular momentum SMUX consisting of spot-based multiplexer and optical mapping network. (d) Spot patterns to sample or emit light. (e) Implementation of OAM SMUX as a Silicon photonic integrated circuit (PIC).

An interesting device, called "photonic-lantern" SMUX, can be considered an extension of a spot-based SMUX. It is theoretically lossless and can support an arbitrary number of modes [42]. Photonic lanterns can merge $N/2$ isolated waveguide modes into one multimode waveguide with N modes through an adiabatic taper. Fig. 4(a) and (b) shows two types of "photonic lantern" SMUXs. The first SMUX, shown in Fig. 4(a), is a vanishing-core photonic lantern [43] created by inserting SMFs into a low-index capillary and tapering it until the single-mode cores disappear and the SMF cladding becomes the new multimode core. The second SMUX, shown in Fig. 4(b), is a laser-inscribed 3-D waveguide SMUX consisting of six coupled cores designed to generate modes that correspond to the modes of a 12-mode FMF. A recent experiment demonstrated that these SMUXs can be built with low loss (< 4 dB). These SMUXs enabled transmission over a fiber supporting 12 modes [27]. The 3-D waveguide technology is especially attractive because it can be used to convert modes between any type of fiber such as MMFs, MCFs, RCFs, linear arrays of SMFs, and others.

Spot-based SMUXs have been integrated using planar waveguides with vertical grating couplers in silicon wire waveguides [44]–[47]. In addition to the spot multiplexer, integrated devices can include an optical mapping network, which allows individual inputs to directly excite fiber modes. An example is the orbital angular momentum (OAM)-based SMUX [44], [45], [48] shown in Fig. 4(c)–(e), to couple single-mode waveguides to the modes of a RCF. It contains an array of beam samplers arranged on a circle and an optical mapping network consisting of an array of path-length matched waveguides and a star coupler (i.e., a planar lens). The path-length-matched waveguides converts azimuthal phase variations to linear phase variations, and the planar lens focuses the linear phase variations to the different outputs. Finally, free-space devices offer full use of all spatial dimensions, which can be used to provide spatial diversity to components such as filters and wavelength switches [37], [49].

3. Outlook

There remain tremendous challenges to be solved before one can truly assess the value of spatial multiplexing in fibers for high-capacity commercial systems. SDM offers the ability to take advantage of the highest degree of optical and electronic integration, a technological path that often led to lower system cost when integrated components can be mass produced and is not performed at the expense of overall performance. Even though the deployment of new optical fibers is necessary before high-capacity space-division multiplexed systems operating over a single fiber strand become a commercial reality, ultimately, it is whether one can achieve a lower cost per bit transported that determines commercial viability. The intense activity in the area of SDM foreseen in the next few years should provide some answers on the future of this technology.

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