Optical Fiber Technology 35 (2017) 108–117

Contents lists available at ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte

High-capacity dense space division multiplexing transmission

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ARTICLE INFO

Article history:
Received 29 April 2016
Revised 27 September 2016
Accepted 28 September 2016
Available online 19 October 2016

Keywords:
Optical fiber communications
Dense space division multiplexing (DSDM)
Multicore fiber (MCF)
Multimode fiber (MMF)
High-capacity transmission
Long-haul transmission

ABSTRACT

In this paper, we review space division multiplexing (SDM) transmission experimental demonstrations and associated technologies. In past years, SDM achieved high capacity transmission through increased spatial multiplicity, and long-haul transmission through improved transmission performance. More recently, dense SDM (DSDM) with a large spatial multiplicity exceeding 30 was demonstrated with multicore technology. Various types of multicore and multimode SDM fibers, amplification, and spatial multi/demultiplexers have helped achieve high-capacity DSDM transmission.

1. Introduction

The transmission capacity in commercial optical fiber communication systems has been increasing at an annual rate of 140%, and the trend is likely to continue because of the expected demand triggered by the introduction of new data communications and high definition video services. The capacity per fiber demonstrated in research and the system capacity per fiber deployed in commercial transport systems are shown in Fig. 1. The maximum transmissible capacity through a single-mode fiber (SMF) has increased approximately 1000, 100, and 10 times through the use of various multiplexing technologies, namely time division multiplexing (TDM), wavelength division multiplexing (WDM), and digital coherent technologies.

As a result of 30 years of systems research, the experimental capacity has reached more than a hundred terabits per second [1,2]. This is considered to be almost the capacity for an SMF because of the maximum input power and the nonlinear Shannon limits [3]. The transmission capacity of commercial transport systems has also continued to increase, and is introduced about 5–10 years after the corresponding research. If the current growth rate is to continue, the commercial capacity may reach its upper limit within the next decade. To meet the demand for higher capacity, new multiplexing technologies are needed that can offer an additional multiplicity of around ten to a hundred times and full compatibility with current TDM, WDM, and digital coherent transmission technologies.

The use of space division multiplexing (SDM) with multicore fiber (MCF) or multimode fiber (MMF) has been proposed as the potential next generation multiplexing technology for optical fiber communications [4]. Over a period of a few years, many transmission studies have been presented that use a variety of SDM fibers possessing multiple cores or supporting multiple modes. Studies on SDM have accelerated and have realized high capacity transmission exceeding petabit/s [5–8], and a high capacity distance product of over 1 Exabit/s $\times$ km [9,10]. Moreover, as a further advancement in spatial multiplexing technology, we have presented dense space division multiplexing (DSDM) [11] with more than 30 spatial channels [11–16]. Recent progress in DSDM transmission systems using multicore and multimode fiber have been reviewed in [17].

In this paper, we expand and update recent studies of high capacity and dense SDM transmission over multicore and/or multimode SDM fibers [17]. Section 2 introduces the progress made on SDM research from the early studies to the current high capacity and dense SDM transmission. Section 3 describes spatial multiplexing technologies in optical fibers, as well as other functional elements in an SDM system. Section 4 presents an overview of SDM transmission experiments and Section 5 concludes the paper with a brief summary.

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http://dx.doi.org/10.1016/j.yofte.2016.09.015
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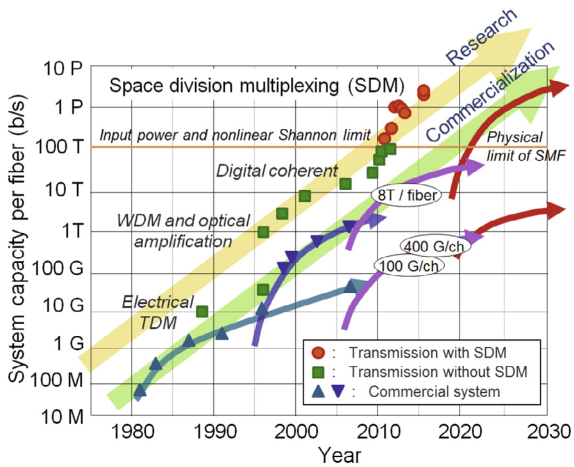

Fig. 1. System capacity per fiber in optical communication systems.

2. High capacity and dense SDM transmission

In this section, we review SDM transmission studies over the past five years, from the early stages in around 2011 to the present high capacity dense SDM transmission.

2.1. Beginning of SDM studies

SDM transmission experiments started with a small number of cores or modes in SDM fibers. Fig. 2 shows the spatial multiplicity in SDM-WDM transmission experiments. Since around 2011, various types of SDM fibers and spatial multi/demultiplexers (MUX/DEMUXs) have been proposed and tested experimentally.

Uncoupled seven-core [18,19] and coupled three-core [20] transmission experiments were performed using free-space optics or fiber bundle fan-in/fan-out (FI/FO) spatial multi/demultiplexing devices. Capacity exceeding 100 Tb/s was demonstrated in seven-core WDM-SDM experiments using polarization division multiplexed (PDM) quadrature phase shift keying (QPSK) modulation with several hundred wavelength channels [18,19]. Long-distance WDM-SDM transmission experiments were also conducted over uncoupled and coupled MCFs.

In early multimode transmissions, few-mode fiber (FMF) was used, which restricts the modes transmissible in a fiber to several low-order modes. Depressed cladding FMF, and then graded index (GI) FMF were used along with differential mode delay (DMD) management, which combines multiple FMFs with opposite DMD characteristics. Phase plate-based mode converters were commonly used for mode multi/demultiplexing, while there are currently various low-loss mode MUX/DEMUXs. Most of the few-mode experiments transmitted a single wavelength or few wavelength channels over a single span of FMF, or multiple FMF spans assisted with conventional single-mode amplifiers [21] or Raman amplification technology [22]. The fundamental multicore and multimode transmission studies undertaken at this stage eventually led to high-capacity and long distance transmission experiments.

2.2. High-capacity transmission in SDM fibers

High-capacity transmission experiments over SDM fibers were realized accompanied by an increase in spatial multiplicity. Fig. 3 shows the capacity and distance of SDM-WDM transmission experiments. A high-capacity 305-Tb/s transmission was realized with a 10.1-km 19-core MCF [23]. We then demonstrated the first petabit/s transmission utilizing a spatial multiplicity of 12 in a low crosstalk 12-core fiber, DWDM with over two hundred wavelength channels, and high spectral efficiency (SE) PDM 32 quadrature amplitude modulation (QAM), yielding a transmission capacity of 1.01 Pb/s [5]. Another transmission was reported with 1.05 Pb/s capacity over a 3-km hybrid MCF containing 12 single-mode cores and two 3-mode cores [6]. These experiments remained the highest capacity per fiber for several years. With a further increase in the number of cores to 22, the capacity was increased to 2.15 Pb/s over 31 km of 22-core MCF [8]. The capacity per core in a multimode transmission also increased from the previous maximum of 57.6 Tb/s over a 119 km span of 3-mode FMF [24] to the current 115.2 Tb/s using 10-mode multiplexing over an 87 km span of MMF [25].

2.3. Long-haul transmission over SDM fibers

The extension of the transmission distance was made possible by improvements in the SDM fiber design and fabrication technique, the development of SDM amplifiers and low-loss spatial MUX/DEMUXs, and the technique for mitigating transmission impairments including crosstalk, DMD, and mode dependent loss (MDL) [26]. A transmission distance of over 100 km was realized by connecting multiple SDM fiber spools or by constructing parallel single-mode or multimode recirculating loop systems. A number of multicore and/or multimode erbium-doped fiber amplifiers (EDFAs) are now available and are being used more extensively in SDM transmission experiments [27–30]. Raman amplification can also be used with SDM fibers or can be jointly used in combination with multimode and/or multicore EDFAs [31].

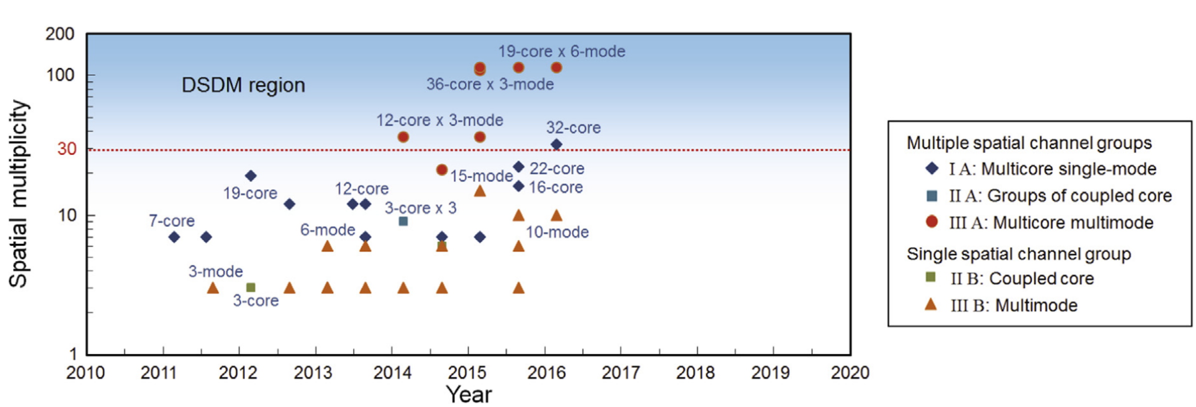

Fig. 2. Spatial multiplicity in SDM-WDM transmission experiments.