Optical Fiber Technology 36 (2017) 155–180

Contents lists available at ScienceDirect

Optical Fiber Technology

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Invited Papers

Space division multiplexing optical communication using few-mode fibers

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ARTICLE INFO

Article history:
Received 5 January 2017
Accepted 20 March 2017

ABSTRACT

To realize ultra-high capacity long-haul transmission, space-division multiplexing (SDM) has emerged as a promising solution, in which each data channel is modulated into an individual spatial/polarization modes in few-mode fibers (FMF) to increase the overall number of parallel channels. In this paper, we review the latest advances in SDM technology on the FMF, component, digital signal processing (DSP), as well as transmission demonstrations. First, we introduce the FMF characteristics, fabrication and manufacturing issues including modal dispersion, mode coupling, and nonlinearities. We next discuss in detail several key SDM components such as spatial multiplexers/demultiplexers (MUX/DeMUX), optical amplifiers, mode converters and SDM reconfigurable optical add-drop multiplexer (ROADM). Accordingly, we explore the DSP algorithms for SDM systems, covering least mean squares (LMS), recursive least squares (RLS), hardware complexity analysis, and mode dependent effects. Besides, a number of recent experimental validations are evaluated enabling higher transmission capacity for short, medium and long distances.

1. Introduction opportunities and challenges

Latest theoretical research has specified that the telecom industry would reach the so-called capacity crunch very soon, for the capacity of demonstrated optical transmission systems based on the conventional single-mode fibers (SMF) is approaching the nonlinear Shannon's capacity limit [1,2]. The space division multiplexing (SDM) technologies have been purposed as an appealing tactic to overcome the capacity crunch, which include mode division multiplexing (MDM) utilizing few-mode fibers (FMF) as well as core multiplexing using multicore fibers (MCF) [3]. Particularly, an FMF allows the propagation of a finite number of higher order spatial modes in conjunction with the fundamental one [4]. One example of refractive index profile comparison between an FMF and a SMF is shown in Fig. 1(a), from which we can see the refractive index difference between fiber core and cladding for a FMF is almost double with regard to a standard single-mode G.652 fiber, prompting FMF with a higher cutoff as well as a larger mode field diameter [5]. The field contours of the first two linearly polarized (LP) modes are displayed in Fig. 1(b), with the arrows representing the two possible polarization directions X and Y. The LP_{11} modes have both polarization and parity degeneracy, while LP_{01} mode has merely polarization degeneracy. By exploring the additional spatial diversity, the mode and/or core amounts can be employed to multiply the bandwidth, henceforward a much higher spectral efficiency (SE) might be achieved in SDM transmission systems than that of SMF [6,7]. Furthermore, FMF exhibits a higher power threshold, as indicated in Fig. 2, than that of a SMF, because the phase noise is intensely impacted by stimulated Brillouin scattering (SBS) and FMF is more tolerant to SBS due to larger core diameter [8].

The extra dimension of spatial mode can be fully compatible with other transmission dimensions, particularly wavelength division multiplexing (WDM), so that SDM using FMF is able to reach its full capacity [9]. If polarization division multiplexing (PDM) is further considered, there would be six distinct modes for Fig. 1 (b) in sum, which are $LP_{01\text{-}X}$, $LP_{01\text{-}Y}$, $LP_{11a\text{-}X}$, $LP_{11a\text{-}Y}$, $LP_{11b\text{-}X}$, and $LP_{11b\text{-}Y}$, when applying MDM-PDM-WDM transmission. The transmitter end schematic of combining MDM with WDM is illustrated in Fig. 3, which depicts that a mode multiplexer (MMUX) should operate over several tens of nanometers [10]. Besides, MDM is compatible with passive optical network (PON), whose schematic structure is provided in Fig. 4 so that signals in various spatial modes can be freely transmitted and received for both downstream and upstream transmission [11]. The bidirectional optical distribution network (ODN) of MDM-PON consists of the passive mode multiplexer/demultiplexer (MUX/DeMUX), FMF and few-mode

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http://dx.doi.org/10.1016/j.yofte.2017.03.009
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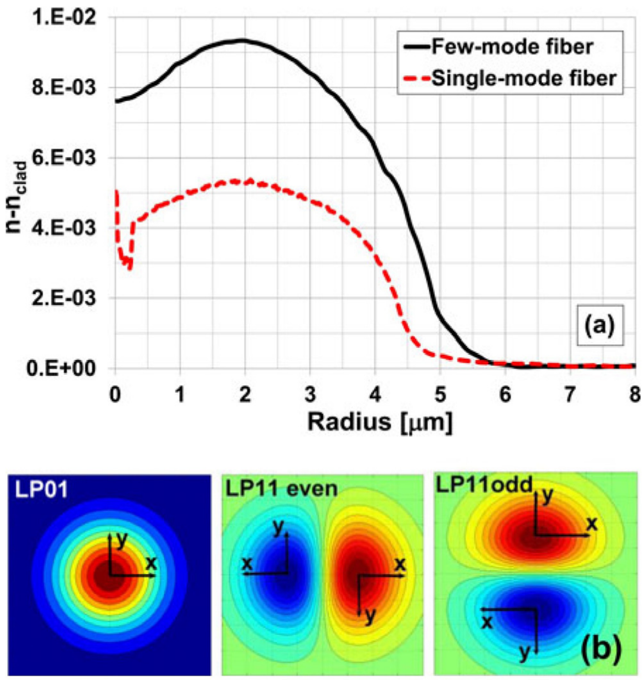

Fig. 1. (a) Comparison of refractive index profile between FMF (black continuous line) and SMF (red dashed line). (b) Field contours of LP_{01} and LP_{11} modes [5]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

circulators. Moreover, SDM technologies find a wide range of applications beyond telecommunication [12]. To quote just a few, the variation of mode phase difference in FMF can be applied to gauge temperature and strain in interferometric sensors [13]. The operating principle of a FMF-based optical performance monitoring system is depicted in Fig. 5, along with the Brillouin frequency shift (BFS) and Brillouin gain spectrum for $LP_{01/11}$ modes [14].

In principle one FMF supporting *m* modes can achieve an *m*-fold network capacity enhancement. Nevertheless, the SDM technologies might still be burdened with quite a few challenges [15]. To begin with, the number of modes supported by a FMF is not only restricted by the fiber design principles, but also limited by the fabrication and manufacturing issues. Secondly, the overall SDM system performance could be degraded by modal dispersion, mode coupling or possible nonlinearities [16]. For instance, in local area

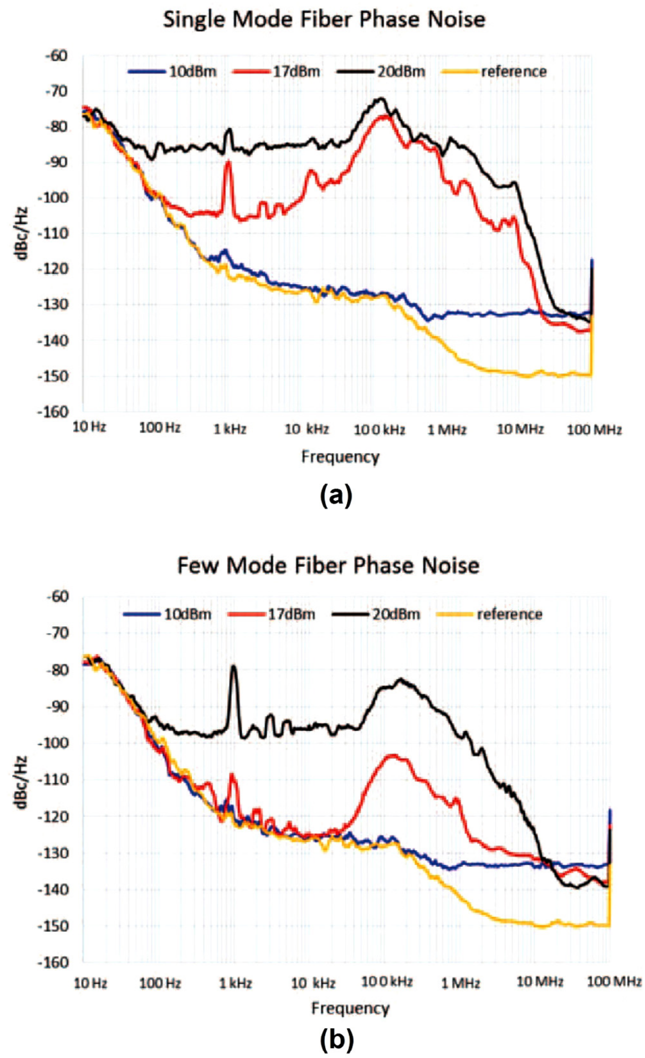

Fig. 2. Phase noise comparison between FMF and SMF [8].

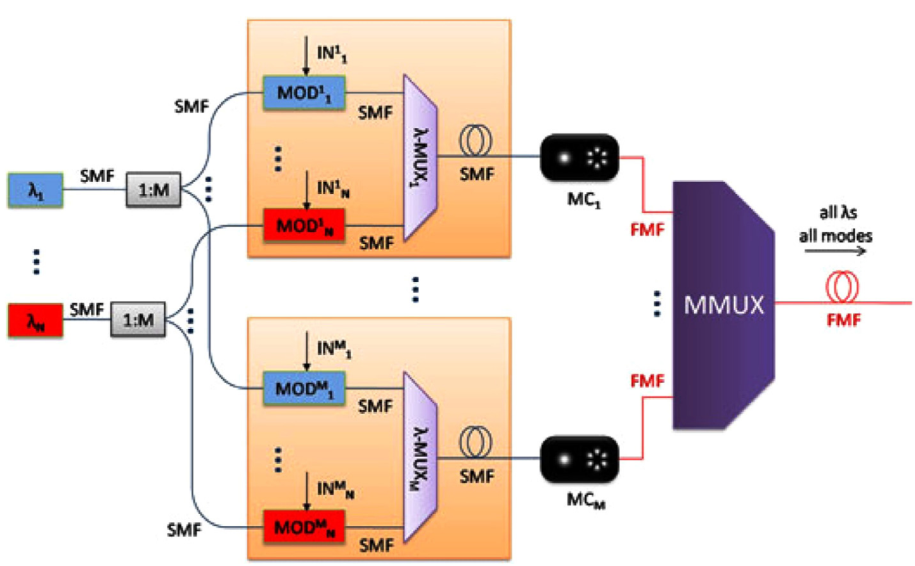

Fig. 3. Transmitter end of MDM using FMF compatible with WDM; λ-MUX, wavelength multiplexer; MC, mode converter; MMUX, mode multiplexer [10].