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ScienceDirect

Procedia Engineering 201 (2017) 148–154

Procedia Engineering

www.elsevier.com/locate/procedia

3rd International Conference “Information Technology and Nanotechnology”, ITNT-2017, 25-27 April 2017, Samara, Russia

Influence of the linear mode coupling on the nonlinear impairments in few-mode fibers

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Abstract

This paper is focused on the influence of the linear mode coupling caused by the fiber bending on the nonlinear distortions in a mode-division multiplexed system. The system under test utilizes the fundamental Gaussian mode and the conjugated first-order vortex modes propagating in the step-index fiber at the same wavelength. For such kind of system, the nonlinear impairments are caused mainly by the cross-phase and self-phase modulations. Propagation of the modal composition is described by the system of generalized coupled nonlinear Schrödinger equations, which serves as a basis of our simulations. Considering the nonlinear operator analytically, we show that it reaches its maximum value due to the power transfer between mode channels caused by the linear mode coupling. Simulation results for equal initial powers in NRZ-coded mode channels demonstrate that nonlinear signal impairments increase significantly for all mode channels in the case of strong linear mode coupling. In the case of weak linear coupling, the increase of nonlinear impairments was also observed, but this effect was appreciably weaker. Moreover, simulations show that the effect described above is stronger for the first-order modes than for the fundamental mode.

Peer-review under responsibility of the scientific committee of the 3rd International Conference “Information Technology and Nanotechnology”.

Keywords: vortex modes; few-mode fibers; Kerr-nonlinearities; mode division multiplexing

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Peer-review under responsibility of the scientific committee of the 3rd International Conference “Information Technology and Nanotechnology”.
10.1016/j.proeng.2017.09.590

1. Introduction

Recent publications in the field of the optical communications capacity show that technologies of single-mode fiber optics are not able to satisfy the growing traffic demand [1, 2]. Optical spatial division multiplexing (SDM) is the promising technology to avoid the capacity crunch, therefore it attracts great attention in recent years [3, 4]. SDM systems are being considered for long-haul systems using coherent detection or short-range systems using direct detection. This technology allows increasing the transmission capacity by multiplexing several signals in the modes of the fiber, so it is often called mode-division multiplexing (MDM). One of the main principal problems for SDM systems is the linear mode coupling that defines strong cross-talk between mode channels [5]. Mode coupling is caused by fiber bending, twisting and inherent optical fiber fabrication defects [6]. It is well known that in the realistic conditions there is strong mode coupling between modes having similar wavenumbers, but their coupling to the modes whose wavenumber is significantly different is much weaker. Previously it was shown that linear mode coupling can be compensated by means of digital signal processing using the "multiple input – multiple output" (MIMO) technology [7, 8]. Alternative approach for the mode coupling compensation can be based on the spatial mode decomposition by means of computer-generated hologram [9]. Another fundamental problem of SDM systems is the nonlinear coupling between the propagating modes [10, 11]. It is evident that nonlinear distortions in the mode channels may sufficiently decrease the efficiency of the linear mode coupling compensation. In this paper, we consider the interaction of the linear and nonlinear mode coupling effects in the case of simultaneous propagation of few spatial fiber modes. In the case of silica fibers, the nonlinear impairments are defined by the third-order Kerr nonlinearities. A number of recent publications were focused on the intermodal four-wave mixing between simultaneously propagating modes on the different wavelengths, that may provide for phase matching [12, 13]. For SDM systems design, the important topic is the investigation of nonlinear transmission of few modes at the same wavelength, when the cross-phase modulation will be the significant origin of nonlinear cross-talk.

Following the approach used to design the mode-division multiplexed system in previous experimental work [9], we investigated signal transmission in standard step-index fiber G.652 in the wavelength region near 850 nm. Such fiber provides propagation of three spatial linearly polarized modes (here we do not consider polarization effects): the two modes LP11 and the fundamental mode LP01.

It was previously shown [14] that measured strength of the nonlinear interaction between the fundamental mode and the first-order modes through cross-phase modulation corresponds to the analytical model based on the propagation of vortex modes LP11+ and LP11–, but not the modes LP11*a* and LP11*b*. Taking this into account, we simulate degenerate LP11 modes in the basis of vortex modes LP11+ and LP11–. Note that the basis of modes LP11+ and LP11– has the property of the same intensity pattern for both degenerate modes and these modes have a helical transverse phase structure of $\exp(il\phi)$, where ϕ is the transverse azimuthal angle and l is the azimuthal order, which is an unbounded integer that indicates the topological charge of the mode.

2. Theoretical background

In the case of simultaneous propagation of N spatial modes one can consider electromagnetic wave in frequency domain as a sum of N items

$$E(r,\phi,z,\omega)=\sum_{p=1}^{N}\exp\left(i\beta_p(\omega)z\right)A_p(z,\omega)F_p(r)\exp\left(im_p\phi\right), \tag{1}$$

where p is the mode number, β_p is the propagation constant of the p-th spatial mode, $F_p(r,\phi) = F_p(r)\exp(im_p\phi)$ is the transverse distribution of the p-th mode field, m_p is the integer number defining azimuthal order of the p-th mode and A_p is the slowly varying amplitude of the p-th mode.

Transmission of the mode superposition in silica fiber in time domain is described by the system of generalized coupled nonlinear Schrödinger equations that might be written as [11]