Optics and Laser Technology 106 (2018) 18–21

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

Influence of mode coupling on three, four and five spatially multiplexed channels in multimode step-index plastic optical fibers

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ARTICLE INFO

Article history:
Received 6 February 2018
Received in revised form 19 March 2018
Accepted 23 March 2018

Keywords:
Plastic optical fibers
Space division multiplexing
Mode coupling

ABSTRACT

We investigate the influence of mode coupling on space division multiplexing capability of three multimode step-index plastic optical fibers with different strengths of mode coupling. Results show that mode coupling significantly limits the fiber length at which the space division multiplexing can be realized with a minimal crosstalk between the neighbor optical channels. Three, four and five spatially multiplexed channels in the investigated multimode step-index plastic optical fibers can be employed with a minimal crosstalk up to the fiber lengths which are about 7%, 5% and 3% of the corresponding coupling lengths (fiber length where equilibrium mode distribution is achieved), respectively. Such characterization of optical fibers should be considered in designing an optical fiber transmission system for space division multiplexing.

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1. Introduction

The increasing demand for digital data bandwidth pushes the development of emerging technologies to increase network capacity, especially for optical fiber infrastructures. The increase capacity of optical fiber systems was caused by successive technology improvements: low losses single-mode fibers, fiber amplifiers, multiplexing, and high-efficiency spectral coding [1]. Multiplexing of optical data can be realized not only in wavelength [2], but also in polarization, in time, in phase and in space [1]. Space division multiplexing (SDM) including mode division multiplexing using multimode fibers or few-mode fibers and/or core multiplexing using multicore fibers, has attracted much attention in the last decade for the next multiplicative capacity growth for optical communication [1,3–8]. SDM may operate at the same wavelength or different wavelengths [9]. In the case of SDM at the same wavelength, radially distributed, dedicated spatial locations are assigned to every SDM channel inside the carrier fiber as these channels traverse the length of the carrier. The location of the each channel inside the fiber is a function of the launch angle and the strength of mode coupling. In practice the channel launched with input angle $\theta_0 = 0°$ along the fiber axis appears as a far field in the form of disk, while all subsequent channels launched with $\theta_0 > 0$ appear in the far field as concentric rings. The center disk and each ring represent a separate spatially modulated optical channel, thereby enhancing the bandwidth of optical fiber systems (see Fig. 1).

Plastic optical fibers (POFs) are a low-cost solution for short-distance applications in digital car networks, industrial networks, and home networks and appliances. Transmission characteristics of multimode step-index (SI) POFs depend upon the differential mode attenuation and rate of mode coupling [9,10]. The latter represents power transfer between neighbor modes caused by fiber impurities and inhomogeneities introduced during the fiber manufacturing process [11]. Mode coupling is very important for SDM because SDM involves tightly packing spatial channels into a fiber, thus making crosstalk between channels an obvious potential problem.

In this work, using the power flow equation, we examine the state of mode coupling in three multimode SI POFs with different strengths of mode coupling, investigated earlier [11,12]. This enables one to obtain the limits of the fiber lengths up to which a SDM can be realized with minimal crosstalk between the co-propagating optical channels.

2. Power flow equation

Assuming that mode coupling in multimode optical fibers occurs predominantly between neighbor modes, Gloge's power

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https://doi.org/10.1016/j.optlastec.2018.03.015

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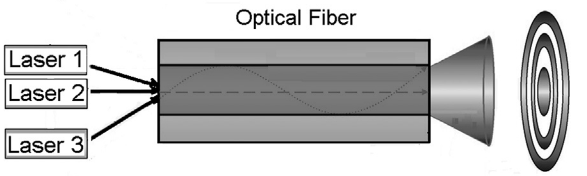

Fig. 1. Minimalistic system design of three channel SDM system.

flow equation for power distribution inside a multimode step-index fiber is [10]:

$$\frac{\partial P(\theta,z)}{\partial z} = -\alpha(\theta)P(\theta,z) + \frac{D}{\theta}\frac{\partial}{\partial\theta}\left(\theta\frac{\partial P(\theta,z)}{\partial\theta}\right) \tag{1}$$

where $P(\theta,z)$ is the angular power distribution, z is distance from the input end of the fiber, θ is the propagation angle with respect to the core axis, D is the coupling coefficient assumed constant [10,13–16] and $\alpha(\theta)$is the modal attenuation. In our previous work [16] we have shown that modeling mode coupling in SI POFs assuming a constant coupling coefficient D can be used instead of the more complicated approach with angle-dependent coupling coefficient. Except near cutoff, the attenuation remains uniform $\alpha(\theta) = \alpha_0$ throughout the region of guided modes $0 \le \theta \le \theta_c$ [14] (it appears in the solution as the multiplication factor $\exp(-\alpha_0 z)$ that also does not depend on θ). Therefore, $\alpha(\theta)$ need not be accounted for when solving (1) for mode coupling and this equation reduces to [15]:

$$\frac{\partial P(\theta,z)}{\partial z} = \frac{D}{\theta}\frac{\partial P(\theta,z)}{\partial\theta} + D\frac{\partial^2 P(\theta,z)}{\partial\theta^2} \tag{2}$$

Numerical solution of the power flow Eq. (2) was obtained using the explicit finite-difference method [15], for Gaussian launch-beam distribution of the form:

$$P(\theta, z=0) = \frac{1}{\sigma\sqrt{2\pi}}\exp\left[-\frac{(\theta-\theta_0)^2}{2\sigma^2}\right] \tag{3}$$

with $0 \le \theta \le \theta_c$, where θ_0 is the mean value of the incidence angle distribution, with the full width at half maximum FWHM = $2\sigma\sqrt{2\ln 2} = 2.355\sigma$ (σ is standard deviation).

3. Results and discussion

In this paper, we analyze mode coupling in three multimode SI POFs used in the experiments reported earlier [11,12]. The three SI POFs had a 1-mm-diameter polymethylmetacrylate core. The fiber HFBR-RUS500 (HFBR fiber) from Hewlett-Packard has an NA = 0.47, the PGU-CD1001-22E (PGU fiber) fiber from Toray has an NA = 0.5 and the ESKA Premier GH 4001P (GH fiber) from Mitsubishi Rayon Co., Ltd. has an NA = 0.51. Critical angles are θ_c = 18.4, 20 and 19.5° for the HFBR, GH and PGU fiber, respectively. It was found that $D = (8.7, 5.6 \text{ and } 3.3)\times10^{-4}$ rad^2/m for the HFBR, GH and PGU fiber, respectively [11,12] – which we have adopted in this work.

In Figs. 2–4, our numerical solution of the power flow equation is presented by showing the evolution of the normalized output power distribution with fiber length for HFBR fiber for five, four and three spatially multiplexed channels, respectively. The five co-propagating optical channels are launched at different input angles θ_0 = 0, 4, 8, 12 and 16° thus maintaining a different spatial orientation. The four co-propagating optical channels are launched at different input angles θ_0 = 0, 5, 10 and 15°, while the three co-propagating optical channels are launched at different input angles θ_0 = 0, 8 and 16°. For multiple optical channels we selected Gaussian launch beam distribution with $(\text{FWHM})_0$ = 0.127° by setting σ_0 = 0.054° in Eq. (3). Ring radiation patterns in very short fibers in Figs. 2(a), 3(a) and 4(a) indicate that the mode coupling is so low thus leading to a minimal crosstalk observed between the neighbor co-propagating optical channels. With increasing a fiber length, a crosstalk between neighbor co-propagating optical channels continue to increase and significantly influence the quality of light signals which are transmitting through the channels (Figs. 2 (b), (c), 3(b), (c) and 4(b), (c)). Finally, at fiber's coupling length L_c the mode-distributions of co-propagating optical channels which

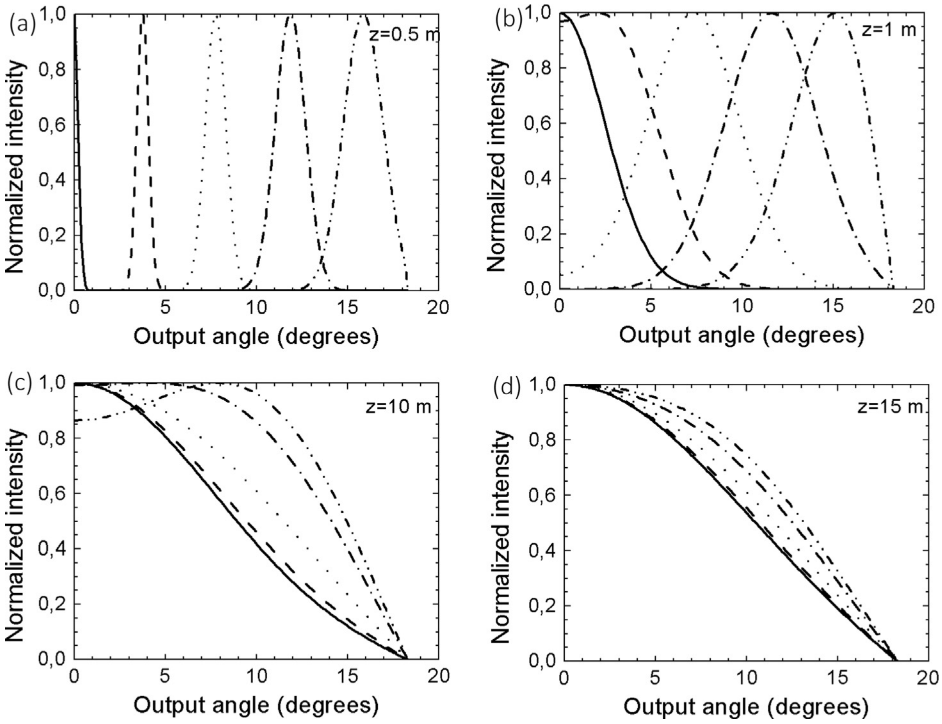

Fig. 2. Normalized output angular power distribution at different locations along the HFBR fiber calculated for five Gaussian input angles θ_0 = 0° (solid line), 4° (dashed line), 8° (dotted line), 12° (dash-dotted line) and 16° (dash-dotted-dotted line) with $(\text{FWHM})_{z=0}$ = 0.127° for: (a) z = 0.5 m; (b) z = 1 m; (c) z = 10 m and (d) z = 15 m.

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