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Selective mode excitation techniques for mode-division multiplexing: A critical review

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A B S T R A C T

Multimode Fiber (MMF) is an established choice for the high-speed backbones in Local Area Networks (LANs). Mode Division Multiplexing (MDM) is an emerging technology utilizing modes as independent data communication channels. MDM controls the delay spread of propagating modes in order to alleviate modal dispersion, which is the principal source of bandwidth limitation in MMF. This paper critically reviews and systematically classifies recent selective mode excitation techniques for mode division multiplexing. The analysis shows that MDM is a viable solution to increase a channel capacity through the combination and separation of the modes at the multiplexer and de-multiplexer.

1. Introduction

The escalation in data traffic has encouraged researchers worldwide to investigate new approaches to increase the capacity of optical fiber backbones [5]. A remarkable bandwidth enhancement technique is MDM, where information is transmitted using the modes in Multimode Fibers (MMFs) [6–15]. This emerging technology offers another dimension for the multiplexing of multiple data channels through a single optical fiber in addition to wavelength [16,17], polarization and time. In MDM, a single mode or groups of modes are used to transmit separate data signals in MMF by precise engineering of the launch field. MDM allows users to control the delay spread of the propagating modes and to optimize the power coupled into each mode. The modes allowed for each channel are excited by matching the incident field of the MMF to the intrinsic modal field of the MMF. On the receiver side, signals will be de-multiplexed by further matching of the modal field to the intrinsic modal field of the MMF, thus optimizing the channel impulse response [18] for distinct channels.

This paper elucidates the various mechanisms for multiplexing and de-multiplexing modes in MDM. Section 2 presents the systematic classification of MDM selective mode excitation techniques. Section 3 discusses the radial offset launch technique, and Section 4 addresses the spatial light modulators approach. Section 5 considers the fiber gratings technique. The phase plate approach is presented in Section 6 followed by the vertical cavity surface emitting laser (VCSEL) array technique in Section 7. Section 8 discusses the photonic crystal fiber technique. Section 9 presents the conclusion of the paper.

2. Materials and methods

2.1. Classification of MDM selective mode excitation techniques

MDM selective mode techniques can be categorized into six methods as shown in Fig. 1. Offset launch is used as an effective means to avoid beam projection on the random geometrical perturbations at the MMF core. Gratings are used to perform the multi-wavelength selection. Phase plates use simple phase masks at both the transmitter and the receiver on the detached glass to achieve the maximum capacity gain. A Spatial Light Modulator (SLM) uses the laser. The VCSEL array was developed to achieve high speed and high efficiency in response to the higher interconnect capacity demands. Finally, the Photonic Crystal Fiber (PCF) technique is used as an optical transmission medium that is characterized as a flexible tailoring of chromatic dispersion over a wide wavelength range.

The following sections explain and discuss each technique separately.

3. MDM by offset launch

Conventional MMF suffers from mode coupling due to random geometrical perturbations in the structure, particularly at the center of the MMF core. Offset launch is an effective means to avoid beam projection on these perturbations at the MMF core. Fig. 2 illustrates the basic principles of offset launch. In offset launch, a small laser beam is projected to a spot radially offset from the core center using a lens [4], a single mode fiber [19] or a spatial light modulator [20].

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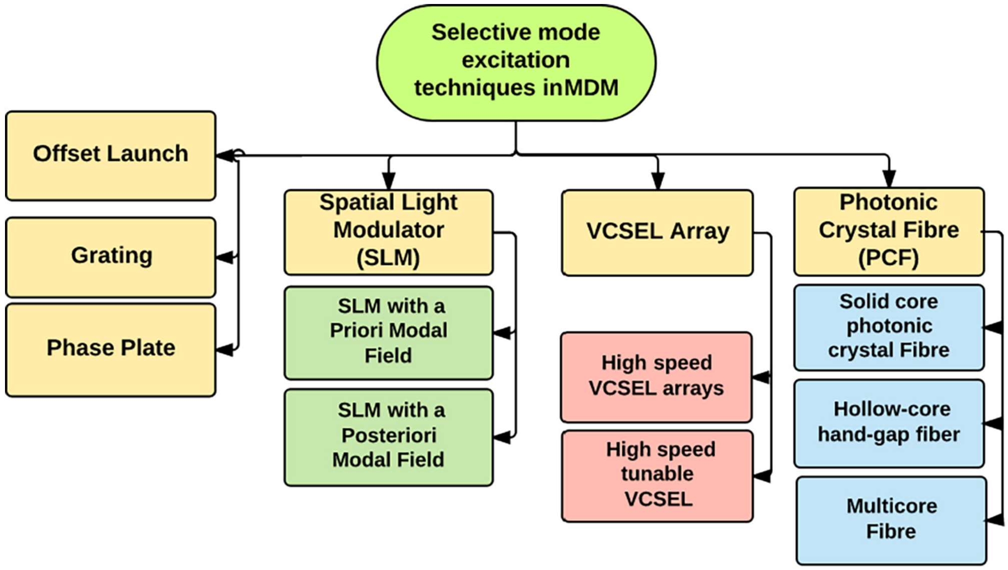

Fig. 1. Classification of MDM selective mode excitation techniques.

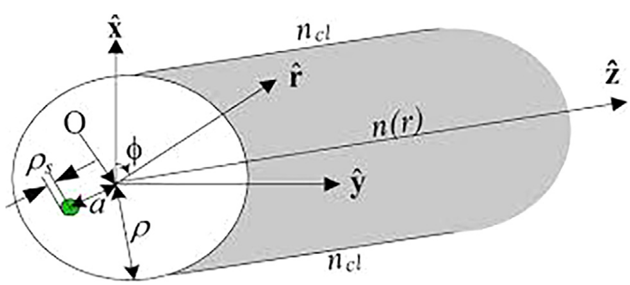

Fig. 2. Offset launch scheme in MMF, *O*: origin of core, *r*: radius of core, ϕ: Azimuthal angle, ρ: distance from the center of the core, ρ_s: radius of the light beam, *a*: radial offset of the spot, *ncl*: refractive index of the cladding, *n(r)* refractive index of core.

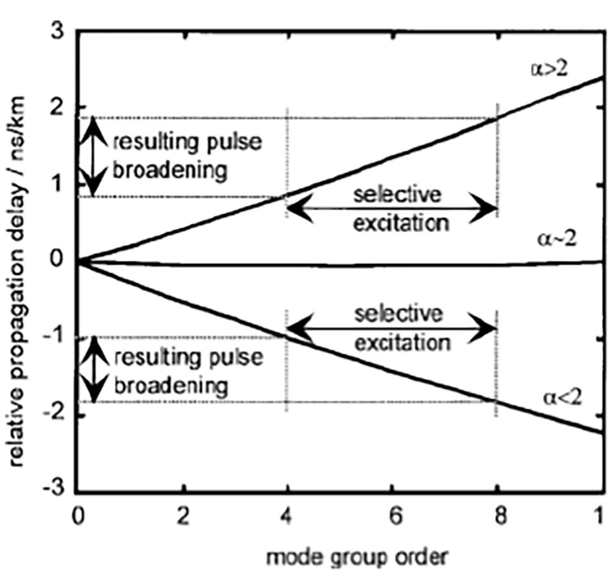

Fig. 3. Propagation delay on the mode group number for fiber indicates the selective excitation and reduced pulse broadening [4].

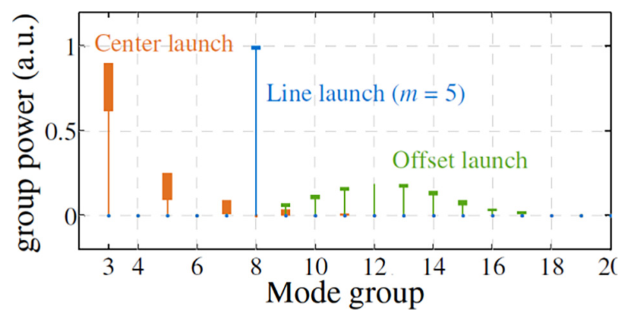

Fig. 4. Fifth HG mode excitation in MMF [21].

This excites only a subset of higher-order modes of the total angular span, which have closer propagation delays. Thus, this technique allows a reduction of the modal dispersion [4,19–21], as shown in Fig. 3. The modal group delays vary directly with the mode number, and thus a reduction in the spread in-group delays and an increase in fiber bandwidth will result from the excitation of only a subset of the modal groups. Carpenter in [22] used binary grating on an SLM to generate offset twin anti-phase spots, allowing adaptive excitation of an anti-symmetric mode group to improve modal dispersion in modal multiplexing. The propagation delay differences for a dual offset launch are shown in Fig. 3. In [23,24], as shown in Fig. 4, a new practical MMF offset launch scheme was used to selectively excite one dimensional fifth-order Hermite–Gaussian (HG) modes using a passive beam shaper formed on a fused silica substrate achieving a transmission data rate of 10Gbit/s over a distance of 220 m of MMF. Later, the first dimension was extended to include two-dimensional square HG (2D) launches. In [26] HG first-order mode, second-order mode, and third-order mode in dual launches achieving 250 m were demonstrated, while in [27] HG (2D) modes were excited achieving a transmission rate of 20 Gb/s over a distance of 250 m. Although significant results have been presented using MDM offset launch, other MDM techniques have been explored and will be explained in other sections.

4. MDM with spatial light modulator (SLM)

SLM can alter the amplitude and phase of the spatial electric field of the laser. An SLM was exploited to design the incident field coupled into an MMF. The rapid reconfiguration rates of the SLM allow agile mode excitations and adaptive updates in the case of channel fluctuations. The desired incident field into an MMF may be coded on the SLM either with a priori knowledge of the theoretical inherent field of the MMF [25,26] or without a priori knowledge by adaptive optimization techniques [27–30]. However, in developing compact, low-loss systems