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Multi-Core Fiber Technology from Design to Deployment

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Abstract *Multi-core fiber (MCF) technology has advanced considerably since the capacity limit of the single-mode fiber had been posed. This talk will review such advancements in the design aspects and deployment trials of MCFs, which have demonstrated technical feasibility of MCF technology in the field. ©2022 The Author(s)*

Introduction

The transmission capacity of single mode fiber has been approaching its fundamental limit in research [1–3]. On the other hand, in new deployments of ultra-high-capacity submarine transmission systems, per-fiber design capacity is now stalled or even decreasing, and fiber count in each cable is rapidly increasing for higher system capacity under limited electric power supply to repeaters from land stations. The number of spatial channels are also increasing in short-reach networks for improving the performances of large-scale data centers (DCs).

In such situations, multi-core fibers (MCFs) are attractive for achieving further higher spatial channel count without increasing cable size and connection footprint. The high spatial channel density of MCFs can also be beneficial to realize thin and light cable [4], which may greatly reduce the cost and environmental load of material, transportation, and installation of new cables.

The concept of MCFs is not so new. The first MCF was proposed in late 1970s when multimode cores were still considered as transmission media for subscriber lines [5,6]. After single-mode fibers became dominant transmission media except for very short-reach links, very limited groups had studied single-mode MCFs for communications from late 1980s to 1990s [7–9]. Since late 2000s, to cope with “capacity crunch” [10,11], the various groups have started intensive research and development of MCFs [12–15], and significant advancements have been made in the MCF technologies.

In this talk, I will give a brief overview on MCF technology progress for optical communications.

Types of MCFs

MCFs can be divided into uncoupled MCFs (UC-MCFS) and strongly-coupled MCFs. UC-MCFs are the MCFs where the crosstalk (XT) between cores is well suppressed so that each core can be used as an isolated spatial channel and is compatible to conventional transceivers. UC-MCFs are sometimes called *weakly-coupled MCFs* or simply *MCFs*. Strongly-coupled MCFs are the MCFs where XT/coupling between cores is not negligible, and can be further divided into randomly-coupled MCFs (RC-MCFs) and systematically-coupled MCFs [16,17].

RC-MCFs are the most major type of strongly-coupled MCFs, in which the modes are strongly and randomly coupled over propagation, and neither supermodes nor local core modes stably propagate without modal coupling [17]. Although random coupling has to be compensated by MIMO DSP, the resultant properties, such as square-root/sublinear accumulations of modal dispersion (MD) and mode-dependent loss (MDL), are beneficial to suppress the calculation complexity and outage probability of MIMO DSP [19,20]. They are considered suitable for long-haul transmissions. RC-MCFs are often called *coupled MCFs*, *coupled-core fibers*, or just *strongly-coupled MCFs*.

Systematically-coupled MCFs are another type of strongly-coupled MCFs with the most strongly coupled cores, which act as a single micro-structured multi-mode waveguide system, supporting supermode propagation. The weakly-coupled supermodes could be used for mode-division multiplexing, but MIMO DSP is likely to be necessary for compensating XT, like few-mode fiber transmissions. So, they have attracted little attention in optical communications.

Today, UC-MCFs and RC-MCFs are two major types of MCFs for optical communications, and most of MCF transmission experiments have been conducted over UC-MCFs or RC-MCFs. Table I summarizes the difference among the MCF types.

Core Layout and Cladding Diameter

Unique features of MCF design are core count, layout, and pitch, to be designed such that the coupling between the cores can be kept to a preferable level and the core density (core count per fiber cross section) can be increased. The core pitch Λ is especially an important design parameter to control the mode coupling between cores both in UC-MCFs and RC-MCFs, as discussed in the following sections. The so-called outer cladding thickness (OCT, the minimum distance between a core center and cladding–

Tab. 1: MCF classification (modified from the tables in **[16,17]**).

Fiber type	**Uncoupled MCF (Weakly-coupled)**	Strongly-coupled MCF	
		Randomly-coupled MCF	Systematically-coupled MCF
Core pitch Λ	**Large**	**Medium**	Small
Mode coupling	**Weak between cores**	**Strong & random**	Weak between supermodes[a]
Dominant source of MD, MDL	**DGD, MDL between cores**	**Both may affect**	DGD, MDL between supermodes
Proportionality of MD, MDL to propagation distance	**Linear between spatial modes (Square root between pol.)**	**Square root (or sublinear)**	Linear

a: Mode coupling between cores is strong and systematic (deterministic). So, we refer to this type as systematically-coupled MCF.

coating interface) is also important to suppress the leakage (power coupling) of the light to the coating in the operation wavelength band [18–20]. A cladding diameter can also be a design parameter to increase the number of cores whilst assuring preferable optical properties [19,21–24]. However, the standard 125-μm cladding with field-proven reliability is a good starting point for early deployments of MCFs [25,26].

Uncoupled MCFs

XT accumulation obeys the coupled power theory, because MCFs are randomly perturbed in their longitudinal direction by bends, twists, birefringence, and so on [14,19,27–30]. Core design and core pitch Λ determine the mode coupling coefficient κ, and are very important parameters, but fiber bend radius R, and the propagation constant mismatch $\Delta\beta$, and correlation length l_c between cores also have impacts on the phase matching between the cores, and hence the XT.

The analytical expressions for XT (or power coupling coefficient h) can be found in [27]. Typical behaviours of XT are summarized in Fig. 1. If an MCF has very identical cores, h monotonically increases with $h \simeq 2\kappa^2 R/(\beta\Lambda)$ at $R < \beta\Lambda l_c$ but asymptotes to $2\kappa^2 l_c$ at $R > \beta\Lambda l_c$. If an MCF has dissimilar cores, the bending radius $R_{pk} = \beta\Lambda/\Delta\beta$ becomes a threshold whether bend-induced phase matching can strongly occur or not [28]. h is approximated by $2\kappa^2 R/(\beta\Lambda)$ at $R << R_{pk}$, and by $2\kappa^2 l_c/[1+(\Delta\beta l_c)^2]$ at $R >> R_{pk}$. The physical interpretation of the relationship between XT and the fiber and perturbation parameters can be found in [28]. The longitudinal fluctuation of refractive index structure had been supposed to be the cause of the perturbation that

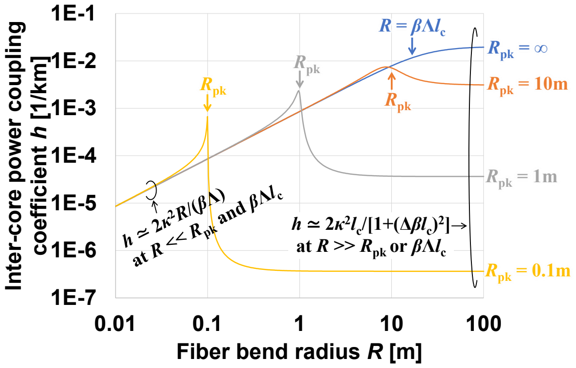


Fig. 1: XT vs fiber bend radius R of 0.01 to 100 m and $\Delta\beta$ corresponding to R_{pk} of ∞, 10 m, 1 m, 0.1 m, at κ = 0.01 m^{-1}, Λ = 40 μm, l_c = 0.1 m, λ = 1.55 μm, $\beta = 1.444(2\pi/\lambda)$.

determines l_c [31], but random fiber twists [32], and birefringence and random polarization coupling [29,30] can more quantitatively explain how those parameters can affect l_c. Microbends also affect l_c [28]. From Fig. 1, one might think that heterogeneous MCFs with smaller R_{pk} are always better because they can realize lower XT in a wide range of R, but small R_{pk} requires large differences in refractive index profiles and optical properties between dissimilar cores. So, heterogeneous MCFs are not necessarily better than homogeneous MCFs, and the trade-off between lower XT and inhomogeneity of cores has to be considered. Therefore, decreasing κ with high confinement cores (high-Δ small-MFD cores, trench-assisted cores, etc.) and a proper Λ is very important for XT suppression.

For long-haul transmissions where the product of signal bandwidth and inter-core skew is sufficiently large, the XT can be regarded as an additive white Gaussian noise on I-Q planes [33–35]. Therefore, based on the GN-model [36], the SNR or fiber capacity under XT can be easily estimated [21,37,38]. Under the linear XT accumulation, 10^{-7} to 10^{-5} km^{-1} is considered as optimum XT level for suppressing SNR penalty and/or maximizing capacity per cross section [26].

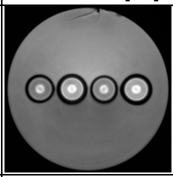
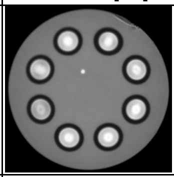
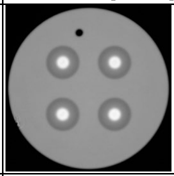
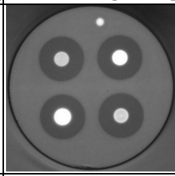
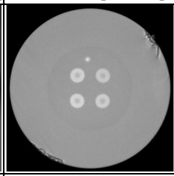
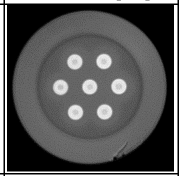
The bidirectional MCF transmission where signals counter-propagate between nearest neighboring cores is a promising technique to suppress the XT and realize performance-improved MCF transmission systems [26]. In such systems, XT still has to be considered because of the effects of Rayleigh backscattering and back reflection from the counter-propagating signals in the nearest neighboring cores, and indirect XT of co-propagating signals via nearest neighboring cores [26,39].

Various UC-MCFs have been designed and reported by considering the above design factors. Table 2 shows some of representative UC-MCFs.

Randomly-coupled MCFs

Accepting random mode mixing, the requirements for core design of RC-MCFs can be much relaxed from UC-MCFs, because very high confinement of light to each core is not necessary to achieve the random mode mixing. So, RC-MCFs are technically more suited to suppressing transmission loss. For enhancing random mode mixing to suppress MD and MDL accumulation,

Tab. 2: Reported MCFs with 125-μm cladding.

MCF Type	UC-MCF				RC-MCF	
	UC-1x4CF [26]	UC-8CF [20]	UC-2x2CF [26,43]	UC-2x2CF [44,45]	RC-4CF [46,47]	RC-7CF [48]
Cross section						
Core pitch Λ	25 μm	~30 μm	40 μm	45 μm	20 μm	23.5 μm
Transmission λ	O band		O-C band	C-L band		
Cable cutoff λ	≤1260 nm			≤1530 nm		
MFD, Aeff	$^{O)}$MFD 8.6 ± 0.4 μm			$^{C)}A_{eff}$ ~80 μm^2	$^{C)}A_{eff}$ ~110 μm^2 (core mode)	
Attenuation	$^{O)}$≤0.40 dB/km			$^{C)}$≤0.18 dB/km	$^{C)}$≤0.16 dB/km	
$^{a)}$XT, MD	$^{O)}$XT ≤ 10^{-4} km^{-1}	$^{O)}$XT ≤ 10^{-4} km^{-1}	$^{O)}$XT ≤ 10^{-5} km^{-1}	$^{C)}$XT ≤ 10^{-6} km^{-1}	$^{C)}$MD ≤ 10ps/√km	$^{C)}$MD ≤ 30ps/√km

a: Co-propagating XT between nearest neighboring cores, O: λ = 1310 nm, C: λ = 1550 nm

designing Λ requires comprehensive consideration taking account of various external perturbations like bends and twist randomness [16,40–42]. However, the earlier studies have indicated that the optimum Λ for random mode mixing ranges from 16 to 30 μm [17]. *R* is also a very important factor on the coupling randomness; therefore, co-design of RC-MCF and cable is important to assure both Λ and *R* can be optimum in deployed condition, as discussed in the following sections.

Table 2 also shows some of representative RC-MCFs. The detailed review on RC-MCF technology is also available in [17].

High-Density Ribbon MCF Cables

State-of-the-art high-density optical fiber cables can accommodates SMFs with very high density thanks to the pliability of partially-bonded fiber ribbons [49], and are widely deployed as optical cables especially for hyperscale DCs and metro networks. MCFs can significantly increase the spatial channel count or decrease the size and weight of such high-density ribbon cables. Pliable fiber ribbons are stranded together in cables, and the bend radius of MCFs can be kept tighter than cable bending, which can supress/control the coupling of UC- and RC-MCFs [24,50]. High-density UC-MCF ribbon cables have been installed in test sites of telecom carriers, and demonstrated low XT and successful signal transmissions even after deployment [25,51,52].

Loose-tube MCF Cables

Loose-tube cables are also often used for small-fiber-count cords/cables that does not need fiber ribbon structures and for ultra-low loss submarine cables. One might think that optical fibers in deployed loose-tube cables are very straight and the MCF coupling characteristics can degrade, but it is not the case. Optical fibers in loose-tube cables are also stranded with slight excess fiber length (for isolating the fibers from external tension to the cables), and stranding and excess fiber length can sufficiently introduce bends to MCFs to control their coupling characteristics [53,54].

In 2019, the first deployment of an MCF cable in a real city was performed with a jelly-filled loose-tube cable [55]. The cable contains UC-MCFs and RC-MCFs, and is available to the research community for SDM transmission trials. The XT of the UC-MCFs and MD of the RC-MCFs are well suppressed after deployment. Detailed characterization of the deployed MCFs and the transmission experiments over the deployed MCFs demonstrated that the transmission channels in the deployed MCFs are sufficiently stable and can transmit signals with negligible errors [56–58].

Recently, the first submarine cable prototype with MCFs was fabricated using the commercial submarine cable design (jelly-filled loose tube) [45]. Cabled UC-MCFs did not show any degradations in optical properties including XT compared to uncabled ones, and successful transmission experiment over the cabled UC-MCFs was demonstrated with negligible Q factor changes due to cabling.

Conclusions

MCF technology has significantly advanced in the last decade or so, and practical MCFs have already been tested in deployed cables, which proves MCFs themselves are technically ready to be deployed. Though this paper focused on the fiber design, cables, and deployments of MCFs, the manufacturing and connection technologies for MCFs have also made a lot of progress toward practical realization and commercial deployments [59–63]. Such continuing R&D progress will make the MCF technology not only technically but economically viable solution to realize high-density/high-channel-count/high-capacity optical communication systems.

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