

Design strategy of uncoupled multicore fiber enabling high spatial capacity transmission

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Abstract—The relationships between fiber parameters and spatial capacity of uncoupled multicore fiber are investigated theoretically. Preferable fiber design and characteristics enabling high spatial capacity transmission is proposed.

Keywords—Multicore fiber; MCF; spatial capacity; spatial spectral efficiency; crosstalk

I. INTRODUCTION

Spatial division multiplexing (SDM) using a multi-core fiber (MCF) is a strong candidate technology to overcome the capacity limit of single-core fiber transmission systems [1]. Recent research has well elucidated various characteristics specific to MCF, such as inter-core crosstalk (XT) [2]–[4], leakage loss of outmost cores [4]–[6], and cutoff wavelength variation due to surrounding cores [7]. Recently, we reported how the XT can affect the signal-to-noise ratio (SNR) in the SDM transmission system using the MCF, and proposed SNR-enhanced MCF [8]. The enhancement of SNR in each core may be one of the ways to enlarge total capacity of the MCF; however, it is not necessarily the way to improve *spatial capacity*, i.e., capacity per cross-sectional area. In this paper, we investigate spectral efficiency (SE) and *spatial* spectral efficiency (SSE) achievable in MCF cores, and propose SSE-enhanced MCF.

II. SIGNAL-TO-NOISE RATIO OF CORES OF MCF

As described in [8], the XT-affected SNR in the MCF core can be analytically expressed by assuming dispersion-uncompensated Nyquist WDM transmission—for approximating nonlinear interference as AWGN—and high symbol rate—for approximating XT as AWGN. Since the Shannon limit of the SE for a polarization mode can be obtained as

$$SE = \log_2 (1 + \text{SNR}), \quad (1)$$

the maximum achievable SE at the optimum input power, hereinafter referred to as SE limit (SE_{lim}), in the MCF can be calculated from the XT-affected SNR. For example, Fig. 1 shows the relationship between the core pitch (Λ), the effective area (A_{eff}), and SE_{lim} at 1550 nm for a step-index core surrounded by its six identical cores in hexagonal lattice. The step-index core was assumed to have attenuation of 0.18 dB/km and the cable cutoff wavelength (λ_{cc}) of 1530 nm. The core Δ and radius depend on A_{eff} , since λ_{cc} is fixed. The calculation assumed 6 dB of EDFA noise figure, 10 THz of whole signal bandwidth, 80-km span length, 3200 km of total length, and fiber bending radius R_b of 1 m. A steep change of

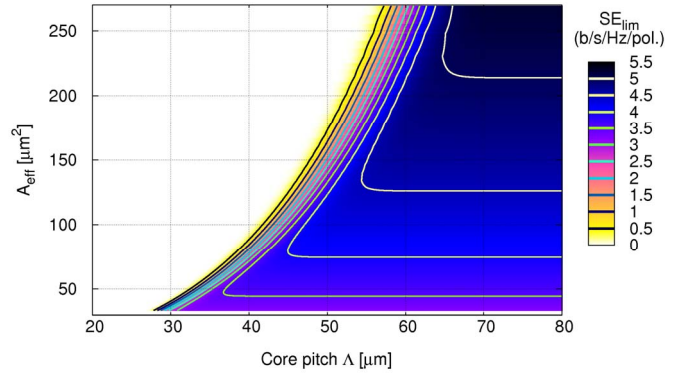


Fig. 1. A relationship between Λ , A_{eff} , and XT-affected SE_{lim} at 1550 nm for hexagonally-arranged step-index cores whose attenuation is 0.18 dB/km and λ_{cc} is 1530 nm.

the SE_{lim} in the horizontal direction is caused by the large dependence of the XT on Λ . We can understand that A_{eff} enlargement improves the SE_{lim} but requires larger Λ for avoiding an XT increase.

III. SPATIAL SPECTRAL EFFICIENCY OF MCF

Based on the relationship shown in Fig. 1, we investigated the spatial spectral efficiency (SSE), which was defined as the aggregate SE per cross-sectional area (A_{cs}) and expressed as:

$$SSE \equiv \sum SE / A_{\text{cs}}. \quad (2)$$

The SSE may be defined for either the bare MCF, the coated MCF, or the MCF cable, by using their aggregate SE and A_{cs} .

A. Potential spatial spectral efficiency of cores

Before considering the SSE limit (SSE_{lim})—that is, SSE obtained from SE_{lim} —for the MCF, we investigate the potential SSE_{lim} of the MCF core, which is defined as the SSE_{lim} where the cores are arranged in the hexagonal lattice on the infinite plane, and can be expressed as:

$$SSE_{\text{lim,core}} \equiv \sum_{\text{core}} SE_{\text{lim}} / (\Lambda^2 \sqrt{3}/2). \quad (3)$$

Figure 2 shows the relationship between Λ , A_{eff} , and the ratio of the $SSE_{\text{lim,core}}$ of step-index cores, divided by SSE_{lim} ($SSE_{\text{lim,SMF}}$) of the SMF whose A_{eff} is $80 \mu\text{m}^2$ at 1550 nm, λ_{cc} is 1260 nm, and coating diameter (D_{coat}) is $250 \mu\text{m}$. For this graph, $SSE_{\text{lim,SMF}}$ is also calculated using Eq. (3) by substituting D_{coat} to Λ . The $SSE_{\text{lim,core}}$ can be 40 times larger than $SSE_{\text{lim,SMF}}$ when A_{eff} is less than $\sim 50 \mu\text{m}^2$, despite the simple structure of the cores.

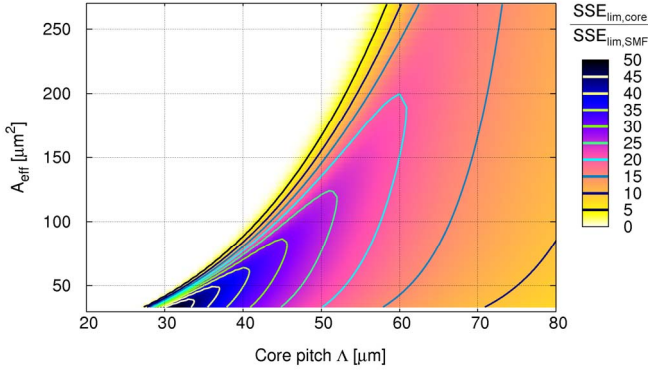


Fig. 2. A relationship between Δ , A_{eff} , and a ratio of potential SSE_{lim} ($\text{SSE}_{\text{lim,core}}$) of the hexagonally-arranged step-index cores, divided by SSE_{lim} ($\text{SSE}_{\text{lim,SMF}}$) of the SSF whose A_{eff} is $80 \mu\text{m}^2$ at 1550 nm and D_{coat} is $250 \mu\text{m}$.

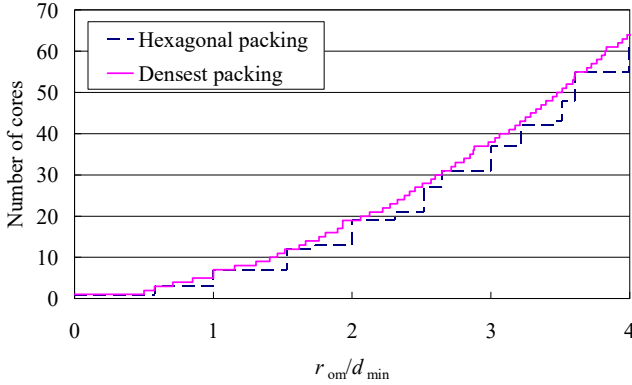


Fig. 3. A relationship between the radial position r_{om} of the center of the outmost core from the fiber center, normalized by the minimum core distance d_{min} , and the number of cores. The densest packing was calculated from [9,10], by reducing the problem to packing equal circles, whose radius is $(d_{\text{min}}/2)/(r_{\text{om}}+d_{\text{min}}/2)$, in a unit circle.

B. Efficient core packing

Since the hexagonal packing of equal circles is the densest in the plane, one might assume that a proper hexagonal core layout can be the optimal packing; however there are cases where non-hexagonal layouts can increase the core count more than hexagonal layouts, because the core-arrangeable area is limited.

The core layout problem can be reduced to the problem of packing circles in a circle, once the cladding diameter (D_{clad}), the outer cladding thickness (D_{coat}), and the minimum core distance (d_{min}) are determined— D_{clad} , OCT, and d_{min} are determined by mechanical reliability and ease of handling, by leakage loss to the coating, and by the XT and cutoff wavelength, respectively. Accordingly, we can leverage the achievements in mathematics [9,10]. Figure 3 shows a relationship between the radial position (r_{om}) of the center of the outmost core from the fiber center, normalized by d_{min} , and the number of cores. It can be seen that the densest packing can effectively utilize a slight increase in r_{om} or a slight decrease in d_{min} for increasing the core count, compared to the hexagonal packing.

C. Spatial spectral efficiency of uncoupled single-mode MCF

Based on the results in Figs. 1 and 3, the SSE_{lim} ($\text{SSE}_{\text{lim,MCF}}$) of the MCF with the densest core packing was

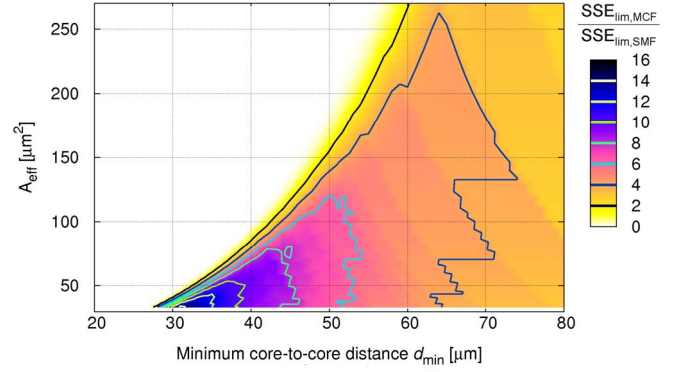


Fig. 4. A relationship between the Δ , A_{eff} , and a ratio of the SSE_{lim} ($\text{SSE}_{\text{lim,MCF}}$) of the MCF divided by that ($\text{SSE}_{\text{lim,SMF}}$) of the SSF. The densest core packing was assumed, and D_{clad} and D_{coat} of the MCF were assumed as $225 \mu\text{m}$ and $350 \mu\text{m}$, respectively.

calculated using $A_{\text{cs}} = \pi(D_{\text{coat}}/2)^2$, and shown in Fig. 4. D_{clad} and D_{coat} of the MCF were assumed to be $225 \mu\text{m}$ and $350 \mu\text{m}$, respectively. The OCT of the MCF was determined so that leakage loss from the outmost core to the coating can be no more than 0.001 dB/km at 1625 nm , thus r_{om} becomes larger when A_{eff} becomes smaller—the power confinement becomes stronger. From Fig. 4, it can be clearly seen that not large A_{eff} but small A_{eff} with moderately short Δ (moderate XT) can enhance the SSE.

So far, we discussed the homogeneous single-mode MCF. However, the heterogeneous MCF with small A_{eff} with moderate XT may have possibilities to further enhance the SSE, if the XT increase in the small bending radius can be suppressed by the high index-mismatch structure, e.g., double cladding structure [11]. Furthermore, similar design strategy—small A_{eff} with moderate XT—can be considered to be applicable to the SSE-enhanced uncoupled MCF with few-mode cores.

IV. CONCLUSION

We investigated SE and SSE that are achievable in the MCF, and proposed SSE-enhanced MCF with small effective-area cores. In the meeting, we will also present the relationship between the XT and SSE, and will discuss the pros/cons of the SNR-enhanced MCF and the SSE-enhanced MCF.

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