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Core Arrangement Optimization of a 12-core Weakly-Coupled Fibre for Unidirectional Transmission

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Abstract—Weakly-coupled multi-core fibres (WC-MCFs) are a strong candidate for short-reach space-division multiplexing; however, inter-core crosstalk (ICXT) remains a primary performance bottleneck for high core-count, being highly dependent on core positioning. In this work, a core arrangement optimization framework based on Sequential Quadratic Programming with a multi-start strategy is proposed to minimize the total ICXT in homogeneous trench-assisted WC-MCFs (TA-WC-MCFs) with a high number of cores for unidirectional transmission, in the C and L-bands. The proposed method identifies an optimal core arrangement of a 12-core WC-MCF, which remains unchanged across different wavelengths and fibre lengths. The optimized arrangement achieves a 0.5 dB ICXT improvement over the best reported in literature, enabling longer link distances.

Index Terms—Inter-Core Crosstalk, Core Arrangement, Sequential Quadratic Programming, Space-Division Multiplexing, Weakly-Coupled Multi-Core Fibres

I. INTRODUCTION

Continuous expansion of cloud services, artificial-intelligence workloads, and hyperscale computing is driving an unprecedented increase in short-reach traffic inside data centres [1]. As intra-rack and inter-rack optical links approach the practical capacity limits of conventional single-mode-fibre systems [2], space-division multiplexing (SDM) has emerged as a key enabling technology [3]. Among SDM solutions, weakly-coupled multi-core fibres (WC-MCFs) are particularly attractive for short-reach links owing to their high spatial parallelism, low digital-signal-processing complexity, and compact form factor [4].

A major limitation in WC-MCF links is inter-core crosstalk (ICXT), which degrades signal quality and limits both transmission reach and core density [4], [5]. In homogeneous TA-WC-MCFs, ICXT is highly sensitive to the spatial arrangement of the cores, making the core arrangement a primary optimization problem [6], [7]. Conventional arrangements,

such as hexagonal, ring, and square, prioritize manufacturing feasibility, rather than ICXT minimization [8]–[10]. The circle packing problem (CPP)-based strategy maximizes the minimum core-pitch (CP) as a proxy for ICXT reduction [6]; however, it treats all core interactions uniformly and does not explicitly minimize total ICXT. The 12-core configuration, the highest feasible core count for standard-cladding TA-WC-MCFs [9], [10], presents a highly nonlinear and non-convex design space in which reaching the optimal arrangement remains challenging.

In this work, we propose a core arrangement optimization framework based on Sequential Quadratic Programming (SQP) [11] with a multi-start strategy to reduce sensitivity to local minima. The optimization directly minimizes the total ICXT of the worst-core in homogeneous TA-WC-MCFs, when cores transmit co-propagating signals (unidirectional transmission), and in C and L-bands, where typical core structure is generally recorder to be smaller [3], [9], making dense core packing more challenging. The goal is to maximize the reach, while maintaining ICXT below the threshold of -23.3 dB assuming 4-PAM short-reach transmission [7]. Results show a consistent 0.5 dB improvement relative to the best CPP-based arrangement, extending the admissible reach to 1 km in the L-band and up to 3.8 km in the C-band, while clearly outperforming other conventional arrangements.

II. OPTIMIZATION METHOD WITH SEQUENTIAL QUADRATIC PROGRAMMING

To obtain low-ICXT in a high-core count WC-MCF inside the standard cladding diameter, the core-center coordinates are jointly optimized under geometric and physical constraints, for unidirectional transmission. The idea is to track the most affected core in each iteration of the optimization method, hereafter referred to as the worst-core, and adjusts all core positions simultaneously, until the core arrangement achieves the lowest ICXT level possible.

The optimization is performed using the SQP algorithm [11] implemented through MATLAB's function `fmincon`. SQP iteratively approximates the nonlinear problem by a sequence of quadratic programming subproblems, handling both the nonlinear objective and nonlinear inequality constraints. SQP is widely regarded as one of the most effective

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methods for constrained nonlinear optimization with smooth objective and constraint functions [12] used in other optics related applications [13]. Unlike gradient-free methods such as genetic algorithms or particle swarm optimization, SQP exploits the smoothness of the ICXT expressions and the constraint functions to achieve convergence near local optima, resulting in significantly faster and more precise convergence [12]. The Hessian of the Lagrangian is approximated using the Broyden–Fletcher–Goldfarb–Shanno (BFGS) quasi-Newton method, which, rather than computing exact second derivatives, constructs a rank-2 update to the Hessian approximation at each iteration [11]

$$\mathbf{B}_{k+1} = \mathbf{B}_k - \frac{\mathbf{B}_k \mathbf{s}_k \mathbf{s}_k^\top \mathbf{B}_k}{\mathbf{s}_k^\top \mathbf{B}_k \mathbf{s}_k} + \frac{\mathbf{y}_k \mathbf{y}_k^\top}{\mathbf{y}_k^\top \mathbf{s}_k}, \quad (1)$$

where k denotes the iteration index of the SQP algorithm, $\mathbf{s}_k = \mathbf{x}_{k+1} - \mathbf{x}_k$ is the step vector and $\mathbf{y}_k = \nabla_{\mathbf{x}} \mathcal{L}_{k+1} - \nabla_{\mathbf{x}} \mathcal{L}_k$ is the change in the gradient of the Lagrangian $\mathcal{L}_k$ between successive iterates $k+1$ and k . Here, $\mathbf{x}_k$ is the variable vector at consecutive iterations, where $\mathbf{x} = [x_1, y_1, \dots, x_N, y_N]^\top$, containing the 2-D core centers in a system that, without loss of generality, the center of the fibre is set at the origin $(0, 0)$. Similarly, $\mathbf{B}_k$ is the Hessian approximation at iteration k , and $\mathbf{B}_{k+1}$ is the updated approximation after incorporating the information from the latest step.

Since the optimization landscape is extremely non-convex, with numerous local minima arising from the nonlinear dependence of ICXT on core-pitches, the SQP-based optimization is executed in a multi-start setting with $K_{\text{start}} = 100$ independent initializations to reduce sensitivity to local minima. This strategy combines computational efficiency of a fast local solver with exploratory power required for non-convex landscapes, and has been established as a robust framework for global optimization of smooth nonlinear programs [12], [13]. For each run, the solver uses a safe maximum of 1000 iterations and 10^5 function evaluations, where the latter limits the total number of objective and constraint calls. The step tolerance was set to 1 nm, which is the convergence criterion for the core center coordinates, determining when to stop after successive iterations. Together, these settings provide a practical balance between numerical accuracy and computational cost for this core arrangement optimization problem.

A. Algorithm

Two manufacturing constraints are imposed, a non-overlapping condition to avoid the physical overlapping between cores, and a boundary confinement constraint. The non-overlapping condition requires the minimum CP between core pairs to satisfy $\Lambda_{\min} \geq 2r_{\text{cs}}$, where $\Lambda_{\min}$ is the minimum CP among core-pairs, and $r_{\text{cs}} = a_1 + w_{\text{in}} + w_{\text{tr}} + g/2$, defines the radius of the core structure. Here, a_1 is the core radius, w_{in} the inner cladding width, w_{tr} the trench width, and the gap between trenches of adjacent cores, g , is set to 3 μm , which corresponds to the minimum allowable separation between adjacent trenches imposed by fabrication limits [5].

The boundary constraint is restricted by the Outer Cladding Thickness (OCT), which limits core placement within the cladding-coating interface and imposes the confinement loss. The boundary radius from the center of the core is given by $r_{\text{OCT}} = D_{\text{fibre}}/2 - \text{OCT}$, where D_{fibre} is the standard cladding diameter of 125 μm .

The random initialization of the core positions considers both constraints; however, it is intentionally less strict with both overlap and boundary condition under a 70% acceptance rate, to enhance exploration, while reducing the number of early iterations spent only on constraint satisfaction. Hence, the nonlinear programming problem to solve, under the previous constraints, is given by

$$\begin{array}{ll} \min_{\mathbf{x}} & \max_i \{f_i(\mathbf{x})\} \quad i = 1, \dots, N \\ \text{s.t.} & |\mathbf{c}_i| \leq r_{\text{OCT}} \\ & \Lambda_{\min} \geq 2r_{\text{cs}} \end{array} \quad (2)$$

where $f_i(\mathbf{x})$ is the fitness function that represents the total ICXT of each individual core i , N is the total number of cores, and $\mathbf{c}_i = (x_i, y_i)$ is the core i center coordinates.

B. Fitness Function

Equation (2) should optimize the ICXT for the worst-core, by choosing among the maximum ICXT between cores. The fitness function contains the total ICXT of each core and considers all relevant ICXT components. To reduce computational cost, the algorithm uses the analytical expressions [3], [5] to compute individual ICXT components. The total ICXT of the affected core i is obtained from the sum of the direct and indirect ICXT are given, respectively, by

$$\text{ICXT}_{\text{dir},i}^{\text{tot}} = \sum_{j,j \neq i} h_{ij} L, \quad (3)$$

$$\text{ICXT}_{\text{indir},i}^{\text{tot}} = \sum_{k,(k \neq i)} \sum_{j,j \neq k} \frac{h_{ik} h_{kj}}{2} L^2, \quad (4)$$

where h_{ij} is the power coupling coefficient (PCC) between core i and core j (h_{ik} and h_{kj} between cores i and k , and k and j , respectively), and L is the link length. Eqs. (3) and (4) are only valid when $h_{ij} L \ll 1$. The PCC between adjacent cores, for small bending radius, is given by [4]

$$h_{ij} = \frac{2k_{ij}^2 R_b}{\beta_i \Lambda_{ij}}, \quad (5)$$

where k_{ij} is the mode coupling coefficient between core i and j , calculated using the analytical expressions presented in [5]. In equation (5), R_b is the bending radius, β_i is the propagation constant of core i , and Λ_{ij} is the CP between cores i and j . The fitness function of equation (2) for core i , is obtained from equations (3) and (4) by

$$f_i(\mathbf{x}) = \text{ICXT}_{\text{dir},i}^{\text{tot}} + \text{ICXT}_{\text{indir},i}^{\text{tot}}. \quad (6)$$

III. RESULTS AND DISCUSSION

In this section, the numerical results obtained, when the SQP algorithm is used for optimizing the WC-MCF core

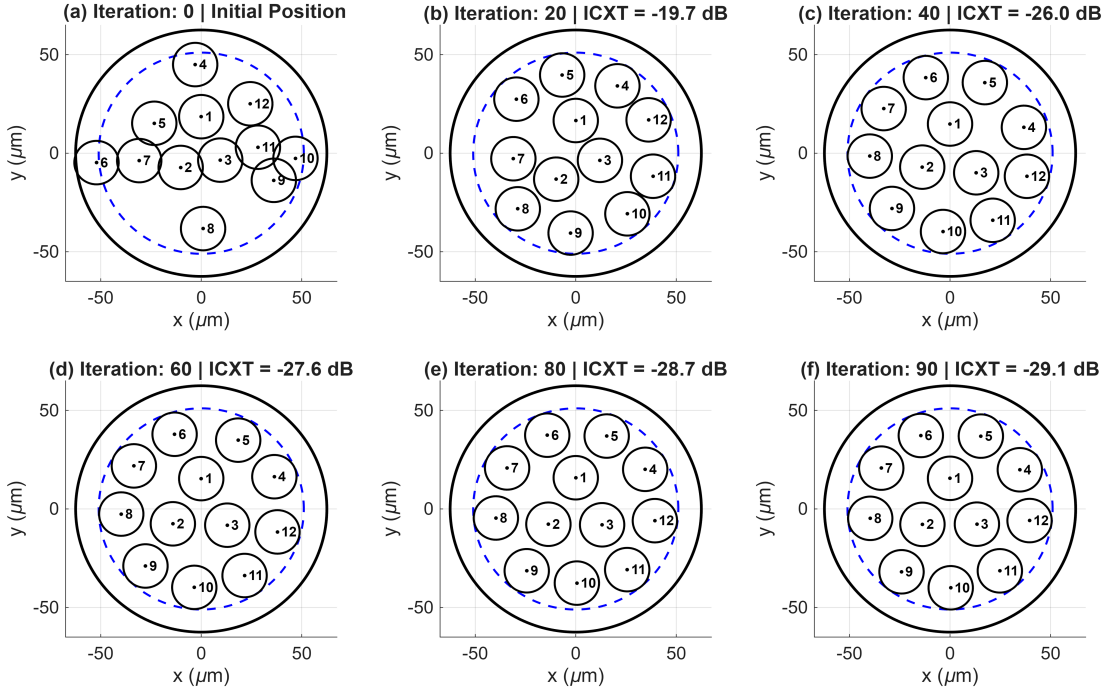


Fig. 1: Core arrangement evolution after iteration (a) 0, (b) 20, (c) 40, (d) 60, (e) 80, and (f) 90, obtained using the SQP method for the 12-core WC-MCF with unidirectional transmission, for $\lambda = 1565$ nm and $L = 1$ km. The blue dashed circles mark the OCT constraint radius r_{OCT} . The final arrangement (f) achieves the lowest ICXT of -29.1 dB after 90 iterations.

arrangement, are presented, with the aim of short-reach link applications and operation in C and L-bands. As ICXT increases at longer wavelengths [3], the upper limits of the C-band at $\lambda = 1565$ nm, and L-band at $\lambda = 1625$ nm are examined. To ensure the feasibility of fabrication of the fibre cores, we use the parameters proposed by F. Zhang in [14], with a core radius $a_1 = 4.14$ μm , an inner cladding width $w_{\text{in}} = 2.04$ μm , a trench width $w_{\text{tr}} = 4.87$ μm , a bending radius $R_b = 140$ mm, and an OCT = 22.5 μm to ensure a confinement loss below 0.01 dB/km. The material of the cladding is pure silica and the refractive index is calculated using the Sellmeier equations at the corresponding wavelength [15]. The core is GeO_2 -doped with refractive index difference $\Delta_c = 0.52\%$ and the trench is F-doped with $\Delta_{\text{tr}} = -0.7\%$.

Figure 1 shows one example of the evolution of the SQP method used in C-band, for $L = 1$ km, every 20 iterations until convergence to the best arrangement shown in Fig. 1 (f) after only 90 iterations. We observe rapid convergence without requiring the full 1,000 iterations to reach the optimum. Multiple starting points converge to similar arrangement, requiring similar number of iterations. This behavior is enabled by the BFGS method, which allows larger step sizes during the initial iterations to efficiently navigate the search space avoiding constraints. This behavior is illustrated in Fig. 1(a)–(c), where the initial iterations do not yield a feasible solution. However, after approximately 40 iterations, the global optimum is almost identified. The subsequent 50 iterations are dedicated to minor rearrangements, further reducing the ICXT.

The method reaches a similar arrangement when applied for

$L = 10$ km, with only hundredth-of- μm coordinate differences and negligible ICXT variation. The optimized arrangement exhibits outer cores (numbered from 4 to 12) arranged in a ring shape with radius r_{OCT} , whose CP varies across different core pairs. The inner cores (1, 2, and 3), which are the most affected by ICXT, are positioned closer to specific outer core pairs, namely (5–6), (8–9), and (11–12), respectively, and exhibit the highest CPs among the outer cores. This spatial arrangement reflects the optimization's tendency to distribute cores according to the dominant coupling interactions. The outer cores 6, 7, and 10, are considered worst-cores with approximately similar total ICXT with the inner cores, while the best core is 12. The total ICXT of the worst-core (1) is -29.1 dB at $L = 1$ km and -19.1 dB at $L = 10$ km.

Table I shows the coordinates of the core centers of Fig. 1 (f) and the level of the direct and indirect ICXT obtained for each core, for $L = 1$ km and $\lambda = 1565$ nm. The direct ICXT exceeds the indirect by at least 33 dB (17 dB for $L = 10$ km), confirming its dominance in unidirectional transmission [4].

A comparison with the arrangement obtained from the CPP approach [6] reveals a very similar configuration, since the optimization is largely governed by direct ICXT, that is highly dependent on the CP. Despite this similarity, the layout shown in Fig. 1 (f) achieves a 0.5 dB total ICXT improvement over the CPP solution for both fibre lengths. This gain arises because the CPP enforces a uniform minimum distance across all neighboring cores, whereas the proposed SQP-based method allows non-uniform CP distribution, providing greater freedom in core placement and effectively minimizing the total ICXT.

Core ID	1	2	3	4	5	6	7	8	9	10	11	12
x (μm)	0.00	-13.73	13.37	34.71	15.33	-14.54	-34.22	-39.72	-24.14	0.33	24.78	39.56
y (μm)	15.53	-7.83	-7.72	19.87	36.94	37.26	20.71	-4.76	-31.89	-40.00	-31.40	-5.90
Direct ICXT (dB)	-29.11	-29.17	-29.20	-30.01	-30.12	-29.55	-29.45	-30.39	-29.87	-29.35	-30.21	-30.84
Indirect ICXT (dB)	-63.80	-63.89	-64.69	-63.50	-63.53	-62.60	-62.39	-63.44	-62.75	-62.44	-63.30	-64.45

TABLE I: Core coordinates of Fig. 1 (f), and direct and indirect ICXT levels of each core for $L = 1$ km at $\lambda = 1565$ nm.

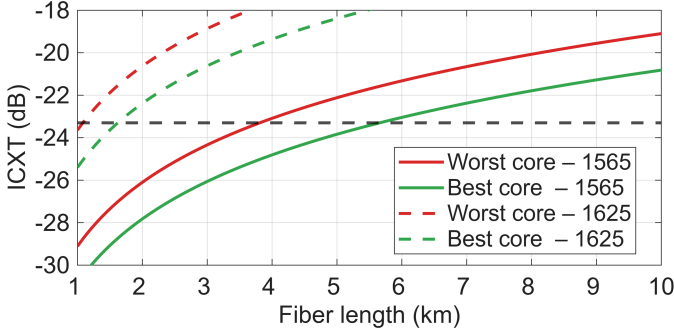


Fig. 2: Total ICXT level as a function of the fibre length for the worst-core (1), and the best core (12) of the core arrangement in Fig. 1, for $\lambda = 1565$ nm and $\lambda = 1625$ nm. Black dotted line indicates the maximum allowed level at -23.3 dB.

The SQP optimization has also been performed in L-band at $\lambda = 1625$ nm, for $L = 1$ km and $L = 10$ km. The optimization process led to an arrangement identical to the one shown in Fig. 1 (f), with only negligible coordinate variations compared to the C-band. Thus, the core arrangement optimisation for unidirectional transmission using the SQP method seems independent of the wavelength and fibre length. The total ICXT level obtained for the worst-core, is -23.6 dB and -13.6 dB, respectively, for $L = 1$ km and $L = 10$ km. Comparing with the CPP-based core arrangement, a 0.5 dB improvement is obtained, similar to the one found in C-band.

Figure 2 shows the total ICXT as a function of the fibre length for the worst-core (1) and best core (12) of the core arrangement in Fig. 1 (f), for $\lambda = 1565$ nm and $\lambda = 1625$ nm. With the proposed arrangement, we achieve an ICXT level lower than -23.3 dB at 1 km in the L-band, and up to 3.8 km in the C-band. In contrast, the CPP-based arrangement exceeds -23.3 dB before 1 km in the L-band, while in the C-band it reaches the threshold approximately at 3.1 km.

Other conventional core arrangements, namely square, hexagonal, and 10-core ring with two inner cores [8]–[10] have also been compared to the arrangement in Fig. 1 (f). All lead to 4.6 dB, 9.8 dB, and 4.2 dB, respectively, higher ICXT level, confirming that SQP optimization leads to an arrangement that substantially outperforms these conventional arrangements. So, they are only suitable for link lengths not exceeding 1.2 km, 0.5 km and 1.3 km, respectively, in C-band.

IV. CONCLUSION

This work presents a multi-start SQP optimization framework for the core arrangement of a homogeneous TA-WC 12-

core fibre with standard cladding diameter, minimizing worst-core ICXT under fabrication constraints for C and L-bands with unidirectional transmission.

The optimized core arrangement achieves a general improvement of 0.5 dB compared to the CPP-based arrangement and enabled transmission up to 1 km in L-band and 3.8 km in C-band, while outperforming other conventional arrangements. Hence, this work shows the effectiveness of the SQP algorithm to optimize the WC-MCF core arrangement for unidirectional transmission. Future work will extend the proposed framework to bidirectional transmission, where counter-propagating cores introduce additional ICXT contributions that fundamentally alter the optimization core arrangement.

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