Journal of Modern Optics

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tmop20

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https://doi.org/10.1080/09500340.2022.2042746

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Design of 31 and 37 cores trench-assisted and air-hole assisted multi-core fibre for high-density space-division multiplexing

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ABSTRACT

In this paper, we have designed two multi-core fibres (MCFs) structures with 31 and 37 trench-assisted and air-hole-assisted cores with reduced inter-core crosstalk (XT). The air-hole pairs and triplets are placed between adjacent trench-assisted cores in order to further suppress modal field overlap. The XT analysis of the 31-core design underlines the significance of enclosing the outer cores with the air-hole structure. The effect of core pitch on the XT is also investigated. Placing the low-index air-hole shield closer to the trench enhances the modal confinement within relatively large trench-assisted core structures. As a result, the lowest possible core-pitch MCF (air-holes touching outer trench boundaries) yielded a minimum inter-core XT of between −60 dB and −70 dB for 100 km of fibre length. Therefore, our 37-core MCF design is suitable for high-density space-division multiplexing applications.

ARTICLE HISTORY
Received 24 August 2021
Accepted 8 February 2022

KEYWORDS
Multi-core fibre; trench-assisted (TA) core; air-assisted hole; MCF Crosstalk; space division multiplexing

1. Introduction

To meet the increasing capacity demands of next generation applications, a need to overcome the capacity crunch of current optical transmission systems drives the market [1]. Space division multiplexing (SDM) is recognized as a possible solution enabling high-capacity data transmission using multi-core fibres that enabled a record capacity of 1 *Pb*/*s* [2]. MCFs have multiple cores enclosed in a single cladding, which increases the transmission capacity by as many folds as the number of cores they have. To increase the number of cores, it is necessary to minimize the core-to-core distance parameter known as core pitch (△) and the distance between the fibre core and cladding known as cladding thickness (CT). However, reducing the core pitch and CT will result in increased crosstalk (XT) between the signals propagated in the different cores. Larger cladding can accommodate more cores, which is undesirable due to several mechanical and structural limitations.

Researchers in Ref. [3] recommended a maximum cladding diameter (CD) of 230 μm to guarantee a failure probability less than 1% over 20 years assuming a minimum bending radius of 60 mm and 200 turns. Trench-assisted cores have been proposed to reduce the crosstalk in MCFs [4–6]. In Ref. [7], a 7-core homogeneous MCF with trench-assisted pure silica cores arranged in hexagonal lattice and offered a crosstalk below −30 dB even after 10,000 *Km* propagation. In Ref. [8], the authors analysed theoretically the performance of 12-core MCF arranged in one ring. They showed that the single-ring structure has better crosstalk performance than hexagonal closed packed structure with crosstalk of −40 dB. In Ref. [9], the authors have designed 12-core and 19-core MCFs used to carry 1 *Pb*/*s*/*fibre*. The crosstalk parameter for a 100 *km* length was −40 dB and −30 dB, respectively.

Employing the air holes between the cores is also an attractive technique for reducing the crosstalk as air-holes creates a wall between cores. MCF with air-hole assisted fibres have been proposed to suppress the inter core crosstalk at least −20 dB in comparison to MCFs without air-holes [10,11]. In Ref. [12], the authors introduced an MCF structure that suppressed unwanted modes and reduced crosstalk to levels below −62 dB. The authors in [13] showed that XT can be further reduced by incorporating air holes between the cores with a trench profiles. In Ref. [14], the authors have illustrated the effect of air holes on crosstalk for a 19-core arranged in different rings and square lattice of 165 μm cladding MCF. They showed that crosstalk can be reduced by 20dB even after adding a single air hole. In Ref. [15],

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Table 1. Characteristics of reported and designed MCFs.

No. of cores	CD(μm)	Core-air-hole arrangement	XT (dB)	References
12	200	Air-trench cores	−55 to 60	[18]
19	200	12 Air-holes on each core	−60	[19]
70	200	6 Air-holes on each core	−46	[2]
07	175	Air-trench cores	−50	[20]
06	125	6 Air-holes on each core	−55.5	[11]
07	192	6 Air-holes on each core	−60	[15]
07	125	6 Air-holes on each core	−45	[21]
19	250	1 Air-hole between each core	−20	[22]
31	200	Triangle lattice	−25	Proposed
37	200	Hexagon lattice	−70	Proposed

the authors have successfully suppressed the crosstalk by −40 and −60 dB for LP_{11} and LP_{01}, respectively. The authors in [16] have achieved low crosstalk by surrounding each trench-assisted core of a 7-core MCF in 192 μm cladding diameter (CD) with six air holes. In Ref. [17], the authors have proposed a 6-core fibre within a 125 μm cladding employing air hole-assisted structure. They maintained a crosstalk lower than −30 dB over 100 *km* fibre.

Researchers in the literature showed that increasing the number of cores result in extremely high crosstalk as adjacent cores will almost touch each other limiting the fibre core density. Moreover, there is a need to add air holes between cores to minimize crosstalk, which also limits the core density in the MCF. A summary of MCF designs in the literature is illustrated in Table 1.

In this work, we propose a novel 31 and 37 core trench-assisted and air-hole assisted MCFs. The cores are place in a hexagon or triangle lattice structure. Also, each core in the structure is surrounded by air holes placed in different ways to suppress crosstalk between the neighbouring cores. The design of the air-hole-assisted MCFs is adjusted to accommodate maximum number of cores with minimum crosstalk within 200 μm cladding diameter.

The theoretical and experimental MCFs as shown in Table 1 proves that placing air-holes between cores is an effective and reliable approach to reduce the crosstalk [19].

The remainder of this paper is arranged as follows. Section 2 discusses the design of the MCF structures. The crosstalk analysis of the proposed design structures is described in Section 3. The analysis of crosstalk suppression using air-hole assisted is discussed in Section 4. Finally, the conclusions are provided in Section 5.

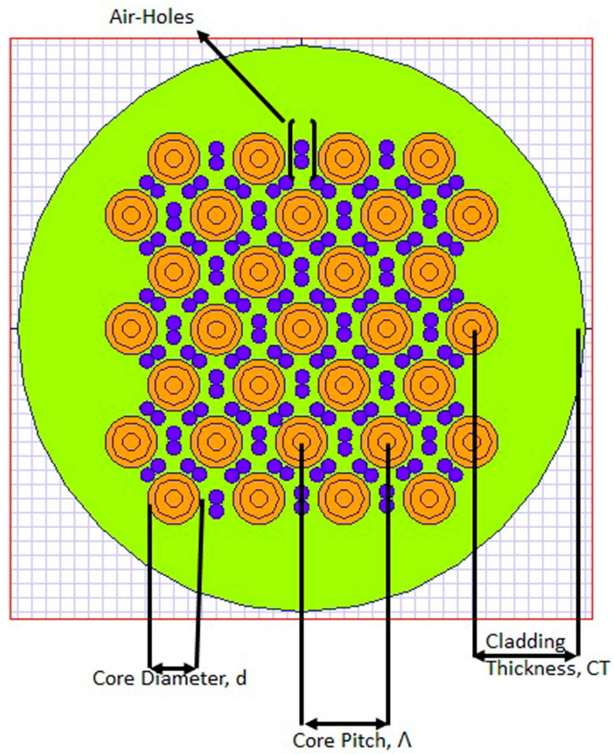

Figure 1. 31 Trench-assisted cores with air holes arranged in triangle lattice.

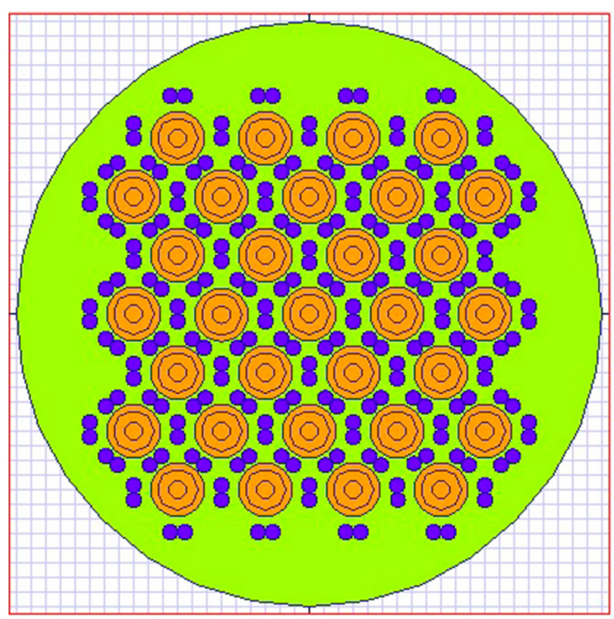

Figure 2. 31 Trench-assisted cores fully surrounded by air holes in triangle lattice.

2. Air-hole assisted trench-assisted MCF design

High-density multi-core fibre structures have been designed with 31-and 37- trench assisted air-hole assisted cores are placed in hexagon and triangle lattice structure

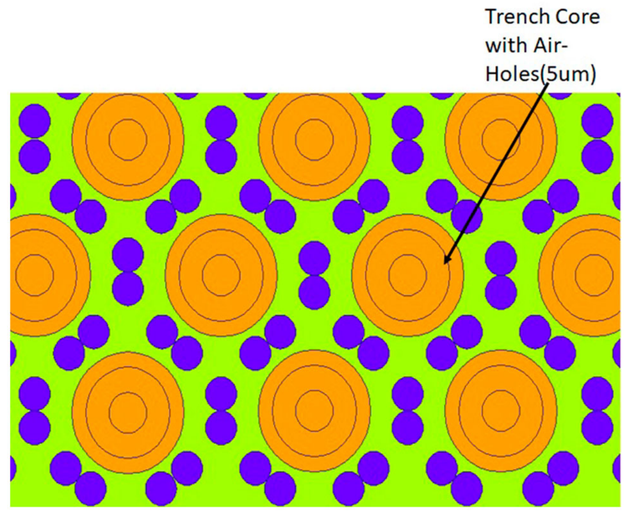

Figure 3. Single core view of 31 trench-assisted cores with air holes.

in cladding diameter of 200 μm as shown in Figures 1–3. Trench-assisted refractive index profile is used to suppresses the overlapping of the electromagnetic fields among the cores which results in suppressed crosstalk. However, air-holes have been placed uniquely in pairs of three on horizontal axis and two on diagonal side. The particularity of our design is the air-hole placement which forms a groove-like structure around the cores, which can evidently prevent the leakage of core energy and isolate the light from other cores. The air-holes are placed in such a manner to minimize their number and achieve minimum crosstalk.The MCF structures having air-holes all around the cores are also good in manufacturability [18,19]. Subsequently, six different MCF designs have been considered in this work; two designs with 31-cores as shown in Figures 1 and 2 and four designs with 37-cores with different horizontal and diagonal core pitch as shown in Table 2. Figure 1 shows the cores along the edges have no air-holes as proposed in Refs [23,24] to minimize the micro-bending losses in outer cores using minimum CT and core pitch. The reduction in the value of CT may increase the bending and confinement losses leading to transmission loss in

Table 2. Designed fibre parameters.

Parameters	Value
Cladding diameter	200 μm
Cladding thickness (CT)	25μm
Core diameter(d)	18 μm
Hole diameter	5 μm
r_1	3 μm
r_2	$1.25 * r_1$=3.75 μm
Trench width (w_t)	$0.75 * r_1$=2.25 μm
Relative R.I.(Δ_1,Δ_2)	0.304%, 0.69%
Cladding Index	1.45
Core Index	1.4544
Trench Index	1.4399

outer cores [25]. Therefore, the values of CT and core pitch are chosen precisely in this work and we have covered all the trench-assisted cores with air-holes as shown in Figures 2 and 3.

Full vector finite element method is used in the simulation of the different designs of MCF structures. Table 2 illustrates the parameters used for the different designs investigated in this work. The core pitch and cladding thickness parameters are mainly varied to accommodate these designs for 31-cores and 37-cores. The core pitch parameter is defined using (Λ_x and Λ_{dig}) parameters shown in the table.

3. Crosstalk analysis

The optimal design parameters summarized in Tables 1 and 3 are used to achieve high-density multi-core fibre structures. When optical power is launched into one core, it will coupled to neighbouring cores during propagation. The inter-core crosstalk (ICXT) parameter is described by Equation (1). IXCT is the one of the main parameters

Table 3. Characteristics of designed MCFs.

Cores	Air-hole arrangement	Λ_x (μm)	Λ_{dig} (μm)	CT (μm)
31	Partially surrounded	30	25	40
31	Fully surrounded	30	25	40
37	Fully surrounded	25	23.585	25
37	Fully surrounded	25	25	25
37	Fully surrounded	23.585	25	25
37	Fully surrounded	23.585	23.585	25

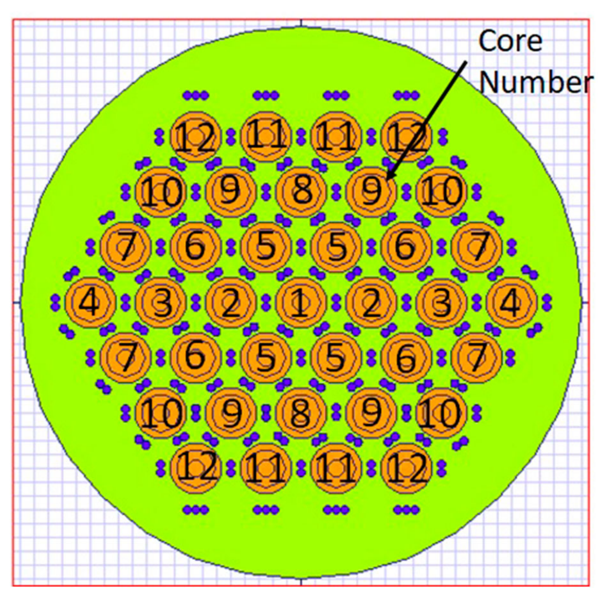

Figure 4. 37 Trench assisted cores with air holes arranged in hexagon lattice.

that needs to be investigated for MCFs.

$$XT = 10\log_{10}\left(\frac{P'}{P}\right)\ \mathrm{d}B, \tag{1}$$

where P and $\acute{P}$ represents the output power from the input and neighbouring core, respectively [26].

The structural parameters of the MCF need to be also optimized to achieve minimum inter-core crosstalk values. The average power in core m at a point z, $P_m(z)$ is defined as [27]

$$P_m(z) = K_{mn}^2 P_n(0) \int_0^z \mathrm{d}\eta \times \left[\int_{-\eta}^{z-\eta} \exp\left(j\Delta\beta'_{mn}\zeta\right) R(\zeta)\,\mathrm{d}\zeta\right]. \tag{2}$$

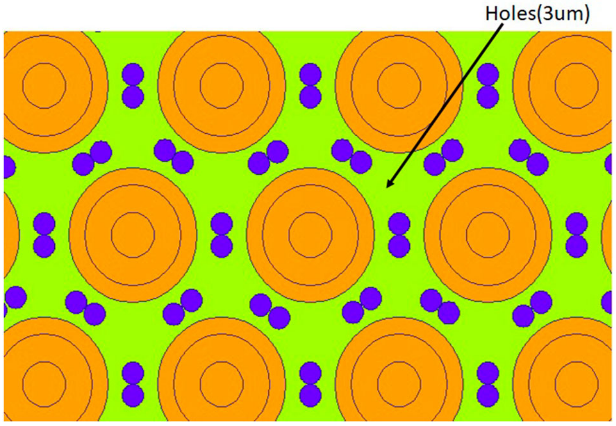

Figure 5. Single core view of 37 trench-assisted cores with air holes.

where K_{mn} is field coupling coefficient, $\Delta\beta_{mn}$ is propagation constant difference between core m and core n and $R(\zeta)$ is autocorrelation function of length ζ. The field profiles for each set of adjacent cores m and n are calculated first using the commercial modes solver FEM offered by OptiMode. The field coupling coefficient parameter K_{mn} is given by [27].

$$K_{mn} = \frac{\omega\varepsilon_0 \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\left(N^2 - N_n^2\right) E_m^*.E_n\,\mathrm{d}x\,\mathrm{d}y}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} U_z.\left(E_m^* H_m + E_m H_m^*\right)\,\mathrm{d}x\,\mathrm{d}y}. \tag{3}$$

The coupling coefficients are used to calculate the average power coupling coefficient (PCC) based on the exponential autocorrelation model assuming a correlation length of 50 mm to get minimum inter-core XT [27]. The PCCs are used to analytically calculate the crosstalk as explained using [27].

$$h_{mn} = \frac{2k_{mn}^2 R_b}{\beta\Lambda}, \tag{4}$$

Therefore, the average crosstalk between the cores m and n can be written as [7]

$$XT \cong h_{mn}L \cong \frac{2k_{mn}^2 R_b}{\beta\Lambda}L, \tag{5}$$

where R_b is the bending radius and L is the length of fibre. Equation (5) shows the dependence of average inter-core crosstalk (ICXT) on bending radius, core pitch, fibre length and mode coupling coefficient. The ICXT is inversely proportional to the effective refractive index and the propagating wavelength.

4. MCF inter-core crosstalk analysis

The inter-core crosstalk for the different MCF structures are calculated and analysed in this section. The ICXT

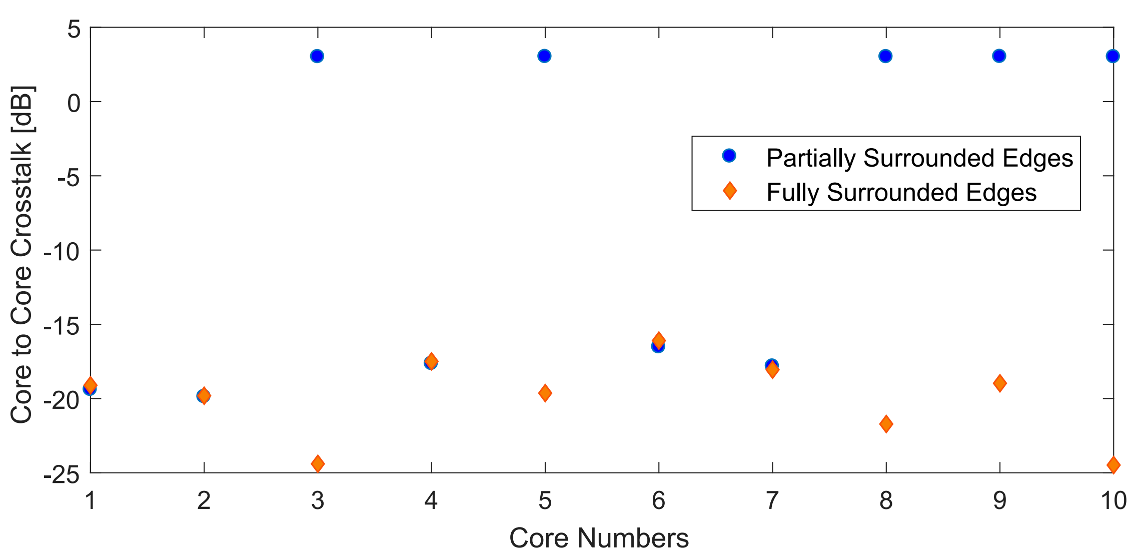

Figure 6. Crosstalk for 31 trench-assisted cores for partially and fully surrounded edges.

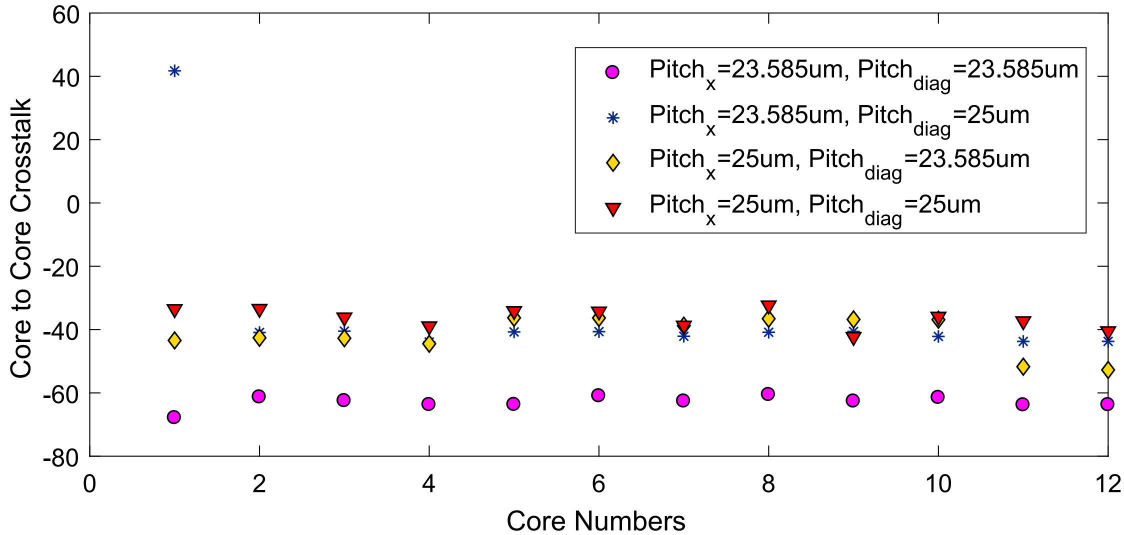

Figure 7. Crosstalk for 37 trench-assisted cores for different core pitch.

parameter is crucial for identifying the maximum possible spatial density of the MCF structure that can be achieved. Based on the symmetry of the designed structures, there are 12 distinct cores combinations in the 37-core structure as shown in Figure 3. Each core has an aureole of air holes that is created to suppress the crosstalk for the structure in 200μm as shown in Figure 5. We have calculated the crosstalk for each core considering all the core pitches for 100 km of fibre length as given in Table 3. Based on the design symmetry for the 31-cores design, there are 10 distinct cores. The ICXT is calculated for both cases of partially surrounded and fully surrounded edge cores as shown in Figure 4. The results shown in Figure 6 and 7 illustrate that the inner cores like 1, 2, 4, 6, 7 and 9 has the same crosstalk for both cases while the cores at edges like 3, 5 and 10 have decreased crosstalk by at least 25 dB for the fully surrounded air-holes case.

The result shows that in spite of reducing the core pitch, the achieved crosstalk can be as low as −40 dB compared to the maximum investigated core pitch. These results show that we can accommodate more number of cores by reducing the core pitch when surrounding each core with air-holes. Up to 20 cores have been placed in CD of 200 um with minimum XT of −60 dB demonstrated in the literature. However, we have successfully placed 37-cores using trench assisted and air-hole assisted in the same CD with a minimum XT of −70 dB.

5. Conclusion

We have designed a 31-core and 37-core trench-assisted air-holes assisted multi-core fibres. We found that the smallest pitch offered the best inter-core crosstalk values. The crosstalk of the minimum pitch value is reduced by −40 dB in comparison with the largest investigated core pitch. This is because of the use of air-holes placed between the cores. As a result, more cores can be accommodated inside the cladding with reduced core pitch even down to 20 μm with air-holes. Otherwise, without air holes, core pitch should be at least 40 μm. The presented analytical model provides a powerful tool for designing high-count homogeneous MCFs as high as 37 trench-assisted cores for optimum CD with the minimum XT of −70 dB for 100 km of fibre length.

Acknowledgments

The authors would also like to thank the anonymous reviewers for the feedback.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The authors would like to thank the “Research project grant to the faculty of DTU” under Delhi Technological University for its financial support of this work under file no. DTU/Council/BOM-AC/Notification/31/2018/5738.

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