Effect of pitch on gain-noise figure and crosstalk performance of T-structured multicore erbium-doped fibre amplifier

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A detailed design scheme is formulated to analyze a novel T-structured Multicore Erbium-Doped Fibre amplifier (MC-EDFA) for future interconnects application within the C-band wavelength. The Fibre amplifier is investigated for different pitches, whereas the cladding radius (R_{ca}) and the core radius (R_{co}) are kept constant throughout the analysis at 125 µm and 10 µm, respectively. The performance of MC-EDFA is analyzed in terms of Gain, Noise figure (NF), and inter-core crosstalk (IC-XT) for three different pitches- 25 µm, 28 µm, and 35 µm. It is found that the novel T-structured MC-EDFA can deliver a noteworthy crosstalk profile by optimizing the pitch.

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Keywords: Multicore Erbium-Doped Fibre Amplifier (MC-EDFA), Mode analysis, Gain, Noise Figure (NF), Inter-core crosstalk

1. Introduction

The need to augment the transmission capacity of optical fibre has encouraged researchers to explore many new approaches to optical fibre transmission systems. This analysis aims to explore the transmission characteristics of an Erbium-doped multicore Fibre amplifier having a T-shaped core arrangement. Comprehensive studies on new types of multicore Fibre (MCF), Multimode Fibre (MMF), and few-mode Fibres (FMF) are available, which uses a different size of the core, numbers of cores, and different arrangement of core layout based on Space Division Multiplexing (SDM) for improved performance of the fibre [1-6]. Various transmission methods were adopted for arranging the core layout for rapidity and high rate of data transfer. Some of the methods are - Uncoupled Multicore transmission, Couple Core transmission, group of channel core transmission, multimode transmission, multicore multimode transmission, Multicore Erbium-Doped Fibre Amplifier (MC-EDFA) transmission [7]. Core layout has also been investigated many times to evaluate the performance of the fibre. The core layout structures mainly adapted by the researcher for designing a MCF are the hexagonal structure, circular structure, square structure, 2×4 core layout, 1×4 core layout, an equilateral triangular structure, etc. Different numbers of cores are being used in different types of core layouts [8]. In the year, 2011 Hayasi et al. [9] have demonstrated a 7-core hexagonal structure fibre with a cladding diameter of 150 µm, mode field diameter (MFD) of 9.8 µm, Effective area A_{eff} of 80 µm within a C-L band operating wavelengths. They have obtained ultra-low crosstalk of 6.0×10^{-9} per km for long- haul application using a cut-off wavelength of $\lambda_{cc} \leqslant 1.55$ µm [9]. After that, in 2012, Hayasi et al. [10] conducted a similar analysis but with an increased cladding diameter of 188 µm, MFD of 12.2 µm, and A_{eff} 124 µm. This resulted in higher crosstalk of about 8.0×10^{-9} per km and a high optical signal to noise ratio (OSNR). Later, in the years 2013 and 2015, Hayasi et al. [11] and Nakanishi et al. [12] have designed a 32 core hexagonal structured fibre with a cladding diameter of 225 µm, A_{eff} of 57 µm within a C-L band operating wavelengths. Both have obtained crosstalk of 9.3×10^{-5} per km and high spectral efficiency using a cut-off wavelength of ~1.47 µm for long-haul application.

Many researchers have investigated various core arrangements other than the most commonly used hexagonal structure. Ryf et al. in the year 2012 [13] designed a microstructure fibre having 3-core and arranged in an equilateral triangular core layout. The cladding diameter considered was 125 µm, and the cut-off wavelength was $\leqslant$ 1.34 µm. In 2014 and 2016, J.K. Mishra et al. designed a rectangular array [14] and triangular profile MCF [15] for interconnecting transmission with low inter-core crosstalk (IC-XT). An uncoupled square core layout fibre structure has been designed by Matsui et al. [16, 17] in 2015 and 2017 using a full wavelength band. They have obtained a crosstalk of 5.0×10^{-5} and 118.5 Tbit/s transmissions over 316 km with a standard cladding diameter of 125 µm and MFD 8.6 µm. In 2017 Hayasi et al. [18] have designed a coupled 4 core square structure fibre using a cladding diameter of 125 µm, A_{eff} as 112 µm, and a cut-off wavelength of $\leqslant$1.47. In that paper, the researchers have focused mainly on coupled MCF for ultra-long-haul transmission and reported low spatial mode dispersion and ultra-low loss coupled multicore fibre for ultra-long-haul transmission. They have achieved 10,000 km transmission with space mode dispersion (SMD) of 3.1 ps/√km. In 2016, Hayasi et al. [19] had used 8-cores circular structures to design an MCF suitable for O-Band short-reach optical interconnects. Furthermore, a 2×4 and 1×4 structure core layout has been designed by Hayashi et al. [20] and Nagashima et al. [21] respectively in the year 2017 for short reach communication. They have used a cladding diameter of 180 µm and 98×200 µm, MFD of 8.4 µm and 9.7 µm, cut off wavelength ⩽1.20 µm and ⩽ 1.34 µm. In a 2×4 Silicon photonics Transceiver crosstalk ⩽ 6.3×10^{-5} per km and 1×4 Multi-Core Fibre with Concaved Double-D Shape Cross Section, crosstalk of 3.0×10−4 per km has been obtained. It can be realized from this literature that the structure of core arrangement plays a vital role in the performance of optical fibre, especially on the crosstalk. It is reported in the available literature that, with the optimal design of the fibre and suitable structure of the core, the crosstalk among the cores can be minimized [22, 23].

From the above discussions, it can be said that literature regarding the different arrangement of core layout in MCF [13-15, 17-21, 24-29] is ample. In conjunction with that, to the best of the author's knowledge, not much has been explored yet for MC-EDFA regarding the structural arrangement of core excluding hexagonal and circular structure for performance analysis. Therefore, in this work, a novel T-structured multicore erbium-doped fibre amplifier has been introduced using 7- cores. The design of T-structured 7-cores MC-EDFA is more preferred for an application like a T-shaped Taper/coupler/splitter [27, 30, 32] for a high range of data rate, capacity density, etc. Zhang et al. have designed an In-Fibre Mach-Zender Interferometer based on novel T-shaped taper and emphasize the use of T-structure in various MCF [32]. In the same line, research needs to be carried out in the field of optical amplifiers. This work aims to initiate the bridging of this gap. The reported results can be helpful in the fabrication and characterization of MC-EDFA to enhance transmission capacity with less coupling loss among the cores.

Depending on various optical interconnect applications, the desirable arrangement of cores in MC-EDFA differs because the properties differ between applications. Consequently, a detailed analysis to study the effect of the core layout on the performance of MC-EDFA is performed. Here, gain analysis, mode analysis, as well as the measurement of inter-core crosstalk (IC-XT) for different pitches, is carried out, and an important conclusion is achieved by comparing the results from the entire analysis. The significant results are compared with the 7-cores hexagonal structured MC-EDFA [34]. The novel design is tested for a constant size of the core (optimized for hexagonal structure [34]) by modulating the distance between the centers of two adjacent cores (ʌ, pitch). The performance of the T-structured MC-EDFA has been analyzed by calculating the gain and the crosstalk through each of the core for a different pitch. In this analysis, the operating wavelength of the C-band range, i.e., 1525 nm – 1565 nm, is used throughout the study. Section 2 briefly describes the structure and the parameters used for designing the Multicore Erbium-Doped Fibre. Section 3 discusses the numerical calculation for MC-EDFA. Section 4 discusses the simulation and the obtained results of the T-structured Multicore Erbium-Doped Fibre Amplifier for performance analysis. Finally, we summarize the findings in Section 5.

2. Design of T-Structured MC-EDFA

In this section, the designing parameters used for constructing the T-structured MC-EDFA comprising of 7-cores are discussed. So far, hexagonal, circular, triangular, etc. arrangement of the core is used for designing a Multicore Erbium-Doped Fibre. Given below Fig. 1 shows the schematic diagram of the T-structured core arrangement of MC-EDFA consisting of 7- cores. For analyzing the T-structured MC-EDFA, the number of cores, size of the cores, pitch differences, outer cladding thickness (OCT), and cladding diameter are important design parameters. Here, OCT is nothing but the minimum distance between the center of the outer cores and the cladding-coating interface. The radius of the core and cladding are kept constant at 10 µm and 125 µm, respectively, throughout the analysis. In this analysis, the effect of pitch differences between the cores is examined for designing the T-structured MC-EDFA. The various pitches used in this analysis are 25 µm, 28 µm, and 35 µm.

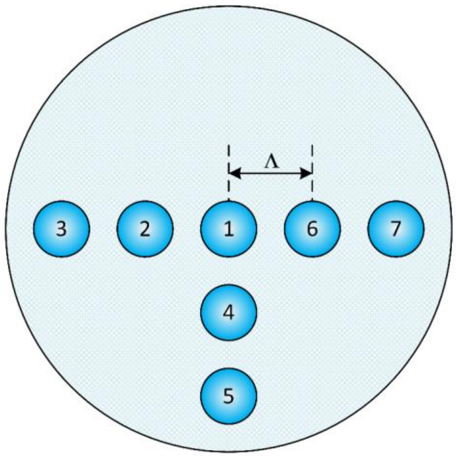


Fig. 1. Schematic of the cross-section of T- structured MC- EDFA (color online)

3. Mathematical model

The respective mathematical equations are solved as written in this section to evaluate the performance of T-structured 7-cores MC-EDFA in terms of gain and NF. Fibre parameters like the R_{co}, NA, R_{ca}, Λ can be optimized through numerical calculation, which will lead to a competent and practical design of a T-structured MC-EDFA. The expression for the intensities of the signal and pump wavelength extract from the light field power, where m = 7 cores are given by [31].

$$I_{(s,m)}(z)=\frac{P_{s,m}(z)\Gamma_s}{A_{core}} \quad , \quad I_P(z)=\frac{P_p(z)\Gamma_p}{A_{core}} \quad \text{and}$$

$$I_{A,m}(\nu_j)=\frac{P_{A,m}(\nu_j)\Gamma_{\nu_j}}{A_{core}} \tag{1}$$

where $P_{A,m}(\nu_j)=P^{+}_{A,m}(\nu_j)+P^{-}_{A,m}(\nu_j)$ (2)

From equation (1), I_p and $I_{s,m}$ are the two intensities of light field traveling through the amplifying medium and interact with the ions. $P_p(z)$ and $P_{s,m}(z)$ are the pump power and signal power at a point at a certain location in the z-direction, respectively. Γ_s and Γ_p are the overlap factors of signal and pump wavelength, respectively. $I_{A,m}$ is the intensity for the amplified spontaneous emission (ASE) component. A_{Core} in the denominator is the cross-sectional area of the core. The pump overlap factor Γ_p is defined as the ratio of the area of the core to the area of the cladding ($A_{Core}/A_{Cladding}$). Here, in equation (2), the term '$P_{A,m}(\nu_j)$ ' is the combination of backward and forward ASE components at a frequency ν_j over a bandwidth of $\Delta\nu_j$. The effective overlap factor 'Γ_s' that represent the overlap among the ions and the light field is given by [33]-

$$\Gamma_s = 1-\exp\left(\frac{-2R_{co}^2}{\omega_0^2}\right) \tag{3}$$

where 'R_{co} ' is the Core Radius. Thereafter, the expression for ω_o is

$$\omega_0 = R_{co}\times(0.65+1.619V^{-1.5}+2.89\times V^{-6}) \tag{4}$$

Here, 'V' is the normalized frequency. Further in this section, a three-level energy system is explained for modeling an MC-EDFA of T-structured at pump wavelength (λ_P) = 980 nm and for longer transmission C-band signal wavelength. $N_{1,m}$, $N_{2,m}$, and $N_{3,m}$ are the population densities of three energy levels, where the population density at level three, i.e., $N_{3,m}$ is considered to be negligible for a practical purpose. Thus, the rate of equation deals with two energy levels system $N_{1,m}$, $N_{2,m}$. for 'm' numbers of the core. So the total population density N_T of erbium doping concentration that remains constant throughout the fibre axis can be expressed-

$$N_T = N_{1,m}(z)+N_{2,m}(z) \quad \text{or} \quad N_{1,m}(z)=N_T-N_{2,m}(z) \tag{5}$$

In a general form, considering m-core EDFA, The second level population density equation at the cores is expressed as [34] "(See Eq (6))".

$$N_{2,m}(z)=\frac{N_T\sum_{s,m=1}^{m=7}\frac{\tau\sigma_s^{(a)}}{h\nu_s}I_{s,m}(z)}{A}+\frac{N_T\sum_{j,m=1}^{m=7}\frac{\tau\sigma_{\nu_j}^{(a)}}{h\nu_j}I_{A,m}(\nu_j)}{A}+\frac{\frac{\tau\sigma_p^{(a)}}{h\nu_p}I_p}{A}N_T \tag{6}$$

where

$$D=1+\sum_{s,m=1}^{m=7}\frac{\tau\left(\sigma_s^{(a)}+\sigma_s^{(e)}\right)}{h\nu_s}I_{s,m}(z)+\sum_{j,m=1}^{m=7}\frac{\tau\left(\sigma_{\nu_j}^{(a)}+\sigma_{\nu_j}^{(e)}\right)}{h\nu_j}I_{A,m}(\nu_j)+\frac{\tau(\sigma_p^{(a)}+\sigma_p^{(e)}}{h\nu_p}I_p \tag{7}$$

The signal and pump intensities I_p and $I_{s,m}$ for 'm' cores are discussed in equation (1) and $I_{A,m}$ is the intensity for ASE component that deals with the parameters A_{Core}, P_P, P_S, $P_A(\nu_j)$, Γ_s and $\Gamma_{\nu j}$. σ_s^a and σ_s^e are the absorption and emission cross-section respectively for the signal wavelength. For 1550 nm signal wavelength $\sigma_s^a = 2.46\times10^{-25}m^2$, $\sigma_s^e = 3.31\times10^{-25}m^2$ and $\sigma_P^a = 1.87\times10^{-25}m^2$ is the absorption cross-section for pump wavelength at the core region doped with ions. σ_P^e, the cross-section for the pump wavelength can be nullified in the further derivation as it is around zero. $\sigma_{\nu_j}^a$ and $\sigma_{\nu_j}^e$ are the two coefficients of absorption and emission for ASE component at frequency ν_j. 'h' is the well-known Planck's constant, τ is the fluorescence lifetime of the higher energy state, $\nu_{s,m}$ is the signal frequency and $\nu_{p,m}$ represents pump frequency. For a multicore fibre, the differential expressions for the pump power, normalized signal power, and ASE distribution in terms of forwarding and backward power are expressed as [33]

$$\frac{dp_p}{dz}=(N_{2,m}\sigma_p^{(e)}-N_{1,m}\sigma_p^{(a)})\Gamma_p P_p \tag{8}$$

$$\frac{dP_{s,m}}{dz}=(N_{2,m}\sigma_s^e-N_{1,m}\sigma_s^a)\Gamma_s P_{s,m} \tag{9}$$

$$\frac{dp^{\pm}_{A,m}(\nu_j)}{dz}(z)=(N_{2,m}\sigma_{\nu_j}^{(e)}-N_{1,m}\sigma_{\nu_j}^{(a)})\Gamma_{\nu_j}P^{\pm}_{A,m}(\nu_j) \pm N_{2,m}\sigma_{\nu_j}^{(e)}\Gamma_{\nu_j}2h\nu_j\Delta\nu_j \tag{10}$$

Thus, for deriving a relationship for the signal amplification among the cores, equation (9) is used. The evolution of pump and signal power through the optical fibre satisfies the following equations, respectively.

$$\frac{dP_{s,m}(z)}{dz}=(N_{2,m}(z)\sigma_s^e-N_{1,m}(z)\sigma_s^a)\Gamma_s P_{s,m}(z) \tag{11}$$

$$\frac{dP_p}{dz} = \sum_m (N_{2,m}\sigma_p^e - N_{1,m}\sigma_p^a)\frac{A_{core}}{A_{cladding}} P_p \qquad (12)$$

After integrating equation (11), the main parameter of MC-EDFA Gain 'G' is calculated, defined as the ratio of output power on the input power expressed in dB. Finally, the gain expression for mth cores is given by

$$G = 10\log_{10}\exp[\int_0^l (N_{2,m}(z)\sigma_s^e - N_{1,m}(z)\sigma_s^a)\Gamma_s dz] \qquad (13)$$

The optical noise figure (NF) is an important characteristic of MC-EDFA. The NF represents a measure of the signal-to-noise ratio (SNR) degradation from the input to the output of the amplifier.

$$NF = \frac{1 + 2\eta_{sp}(\lambda)[G-1]}{G} \qquad (14)$$

For MC-EDFA, the spontaneous emission factor depends upon the cross-section ratio, $\eta_{sp} = \frac{\sigma_e}{\sigma_a}$ at both pump and signal wavelength. '$\eta_{sp}(\lambda)$' is always greater than or equal to unity. The fundamental result for NF of a high gain amplifier is always greater than '2'.

4. Simulation and results

This analysis is simulated using COMSOL Multiphysics to study the mode analysis of 7- cores T-structured MC-EDFA. Several parameters are being considered, and numerical calculation is done as discussed in section 3 to examine the performance of T-structured MC-EDFA in terms of gain and NF. Also calculated IC-XT for three different pitches, 25 µm, 28 µm, and 35 µm between the cores. For performance analysis, gain and NF through each of the core have been determined regarding different operating wavelengths. Different wavelengths within the range of 1525 nm to 1565 nm are used as signal wavelength, which is joined with 980 nm named pump wavelength for three different pitch values as mentioned above. The input signal power and pump power are kept constant at 0.001 W and 7.6 mW for each core of the T-structured MC-EDFA. Further, for the 15 m length of the fibre the material is chosen in such a way that the concentration of the doped erbium remains constant at $7\times10^{24}/m^3$ throughout the analysis. Besides, this model is simulated by keeping the size of the core constant, whereas the pitch is varied to get a clear picture of its effect on the performance of MC-EDFA. The performance analysis is also accompanied by mode analysis, the IC-XT among the neighboring core for three different pitches, i.e., 25 µm, 28 µm, and 35 µm, to find out the suitable geometrical condition for the stronger performance of the T-structure MC-EDFA.

4.1. Performance Analysis of T-Structured 7-Cores EDFA

In this Section, Fig. 2, 3, and 4 depict the gain profiles through each core for the pitches of 25 µm, 28 µm, and 35 µm, respectively. In all three cases, it can be seen that the gain profile for each core is different and follows the trend, which increases steeply, then stabilizes, and finally shows a steep decrease. Fig. 2 depicts the variation of gain and NF with wavelength, considering 25 µm as pitch, core size as 10 µm, and the cladding size as 125 µm. The core and the cladding size are kept constant for the rest of the two pitches, i.e., 28 µm and 35 µm. For a 25 µm pitch difference, the maximal amount of gain attained is 41 dB at 1550 nm. For the same pitch difference, the minimum gain attained is 12.33 dB at 1525 nm. Variation in the amount of gain is observed through different core due to the pitch difference among the neighboring core. For 25 µm pitch difference at R_{co} = 10 µm, the NF obtained is within the range of 6.24 - 8.99 dB. For 28 µm pitch difference in Fig. 3 maximum gain of around 42 dB is attained in the center core at a wavelength of 1550 nm. This is nearly equal to the mostly used hexagonal structure [33]. Also, for Λ= 28 µm, the minimal amount of gain 13.13 dB is attained at 1525 nm operating wavelength. Also, the NF obtained for Λ= 28 µm as shown in Fig. 3, is within the range of 6.23 – 8.69 dB. The maximal amount of gain attained in the case of 35 µm pitch distance is approximately 41 dB, and the minimal amount of gain is found to be approximately 15.27 µm at 1550 nm and 1525 nm operating wavelengths, respectively as shown in Fig. 4. The NF obtained for the pitch value of 35 µm is within the range of 6.28 – 9.35 dB. From the entire gain and NF graphs, it is clear that the 28 µm pitch is suitable for the proposed T- structured core with a designing parameter of R_{co}= 10 µm and R_{ca} = 125 µm. In the pitch difference of 28 µm, the amount of gain obtained is a mere 2.44% higher in comparison to 25 µm and 35 µm pitch. This is because when the pitch reduces more, say to 25 µm, the cores come closer to each other, due to which interference tends to take place. Similarly, as the pitch is spread to 35 µm pitch, the core gets spread out and gets nearer to the boundary of the cladding, due to which not maximum amount of gain is obtained through all the cores. The obtained gain results are compared with that of the 7-core hexagonal structure MC-EDFA to ascertain the performance of the used fibre, [33]. The T-structure MC-EDFA possesses R_{co}= 10 µm, R_{ca}= 125 µm, Λ= 28 µm provide maximum gain (42 dB), which is almost equal to the reported gain of the 7-core hexagonal structure MC-EDFA which is 42.09 dB [33]. The difference between both is just 0.21% which is negligible. The entire different configurations are broadly investigated and discussed in section 4.2. Out of all the three configurations, the best geometric configuration in terms of gain, NF, and mode analysis is used for the measurement of IC-XT to further confirm its quality and efficiency.

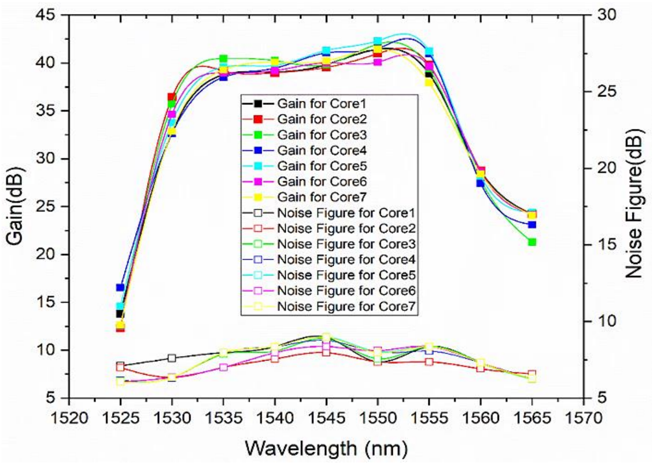


Fig. 2. Variation of Gain and Noise Figure with Wavelength for 25µm pitch (color online)

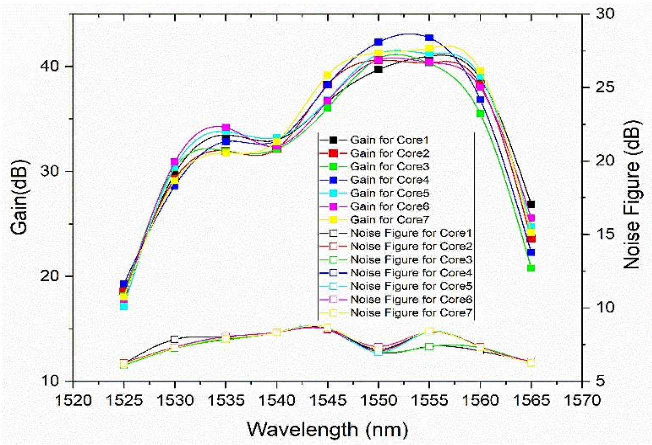


Fig. 3. Variation of Gain and Noise Figure with Wavelength for 28 µm pitch (color online)

Table 1. The maximum and minimum gain obtained for different pitch between the cores for 10 µm radius of the core

Pitch	Maximum Gain	Minimum Gain
25 µm	41.00 dB	12.33 dB
28µm	42.00 dB	13.13 dB
35 µm	41.00 dB	15.27 dB

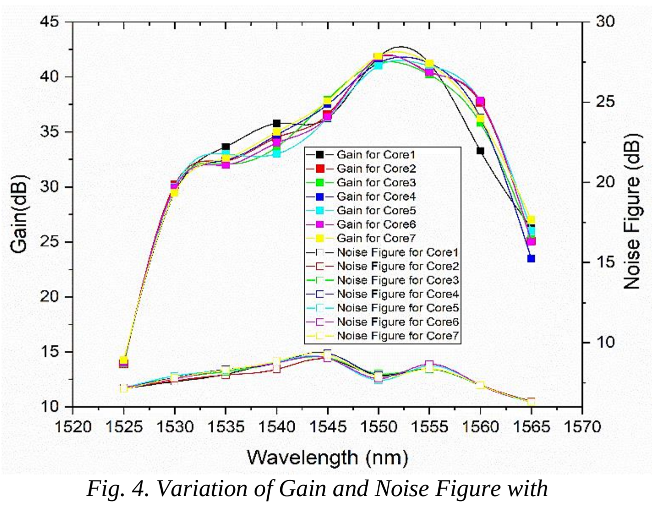


Fig. 4. Variation of Gain and Noise Figure with Wavelength for 35µm pitch (color online)

4.2. Mode Analysis of T-Structured 7-Cores EDFA

In addition to the above study, fibre performance is also analyzed using mode analysis. This is conducted in COMSOL Multiphysics for three different pitches considered for the study and a range of signal wavelengths. All the parameters, including the geometric parameters used in this investigation, are the same as those used in the gain and NF analysis. The core radius is kept constant, and the pitch between the cores is varied.

Table 2 shows the comparison of the mode profile among three different pitches to the operating wavelength ranges from 1525 nm to 1565 nm, which are represented as Case1, Case2, Case3 in further discussions. For each pitch difference and wavelength considered, various mode patterns are seen to be propagating through the cores. For Case1, i.e., 25 µm pitch difference between the cores, LP_{61} mode is observed within the cores at wavelength 1525 nm and 1530 nm. At 1535 nm, LP_{02} mode is seen traveling through all the cores using a pitch difference of 25 µm. As soon as the operating wavelength increased from 1540 nm to 1565 nm, LP_{12} modes with a maximum amount of light are seen passing through the cores. But in Case 2, Λ= 28 µm, LP_{12} modes are traveling through the entire operating wavelength except at 1535 nm wavelength. At 1535 nm operating wavelength, LP_{02} mode is propagating through all the cores. At last, in Case 3, for pitch difference 35 µm, both high intensity and low intensity of LP_{02} modes are seen traveling through different cores for operating wavelength 1525 nm to 1535 nm as shown in Table 2. Then with the increment of wavelength from 1545 nm to 1565 nm, a combination of high and low intensity of LP_{12} modes is traveling through all the cores. Thus, from the comparison of mode analysis among three different pitches between the core, i.e., 25 µm, 28 µm, and 35 µm, LP_{12} modes are found to be the dominating mode. At 28 µm pitch difference, the better intensity of LP_{12} modes is observed through almost all the signal wavelengths.

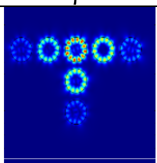
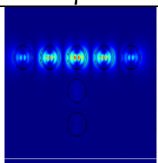
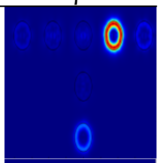
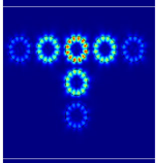
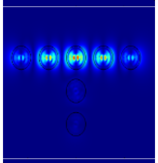
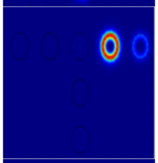
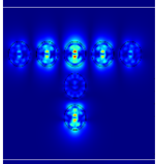
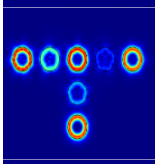
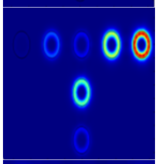
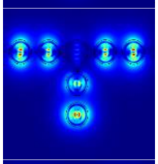
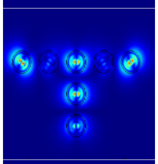
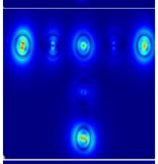
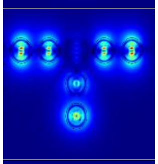
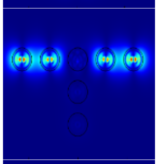
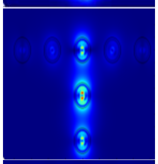
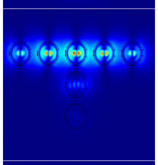
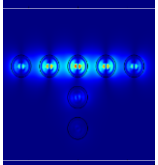
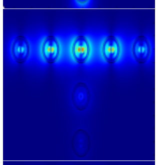
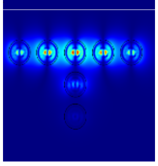
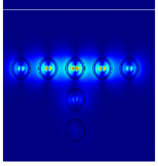
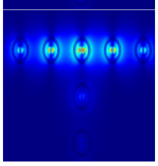
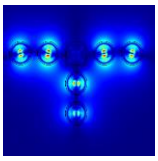
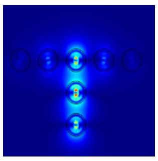
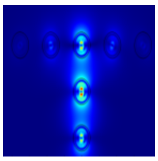
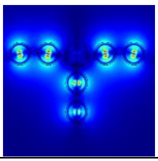
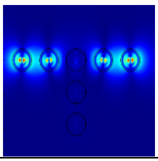
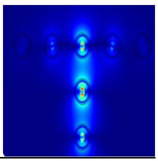
On comparing the mode analysis results of 7 core T-structure with that of hexagonal structure [33] having R_{co}= 10 µm and Λ= 28 µm, the T-structure provides the better intensity of mode through all the cores with less dispersion. LP_{12} mode is the dominating mode in both the structures, and therefore it can be concluded that both the structures provide comparable performance in terms of mode too.

4.3. Crosstalk analysis for three different pitches

In this section, the inter-core crosstalk (IC-XT) among the three different pitches, i.e., 25 µm, 28 µm, and 35 µm between the cores, has been evaluated. Calculating the IC-XT among the neighboring cores is a crucial issue because low IC-XT allows information to reach longer distances, with minimum loss taking place among the adjacent cores during the propagation. Here the variation of pitches among the cores concerning the IC-XT has been investigated to develop a relationship between pitch *a*nd the IC-XT. For calculating IC-XT, measuring power through all the cores is necessary. The IC-XT in dB is calculated by the following mathematical expression:

$$\text{IC-XT (dB)} = 10\log_{10}\left(P_{coreA} \Big/ \left(P_{coreA-coreB}\right)\right)\Bigg|_{A\neq B} \tag{15}$$

Table 2. Determination of mode profile for different pitches over C-band wavelength (color online)

Wavelength	25 µm	28 µm	35 µm
1525 nm			
1530 nm			
1535 nm			
1540 nm			
1545 nm			
1550 nm			
1555 nm			
1560 nm			
1565 nm			

Here, $P_{coreA-coreB}$ is the power coming from core A to core B concerning the considered geometry; if we consider core 1 as core A and P_{coreA} is the power through core 1, then P_{coreB} will be power transmitted through core2, core3, core4, core5, core6, and core7. IC-XT is thus defined as the ratio of the power coming from the reference core to that of the rest of the cores [34]. Fig. 5, Fig. 6 and Fig. 7 show the interpretation graph of IC-XT of pitch difference- 25 µm, 28 µm, and 35 µm at a wavelength of 1550 nm for T- structured 10 µm size of the core. After conducting the calculation, the IC-XT at 1550 nm for all the three pitches are found to be: -42.48 dB, -47.85 dB, and -50.70 dB per 15 m length of the fibre, as shown in Table 3. From Table 3, Fig. 5, Fig. 6, and Fig. 7, it is clear that when the distance shrinks between core to core, it results in a large IC-XT. Thus with the substantial increment of the core to core distance, XT decreases rapidly. From this analysis, we can notify the fact that, for the proposed geometrical condition of T-structured 7-cores MC-EDFA, 35 µm (higher) pitch difference among the core is suitable for operation.

Table 3. Inter-core Crosstalk for different pitches between the cores for a 10 µm radius of the core

Pitch	Inter-Core Crosstalk (IC-XT)
25 µm	-42.48 dB
28 µm	-47.85 dB
35 µm	-50.70 dB

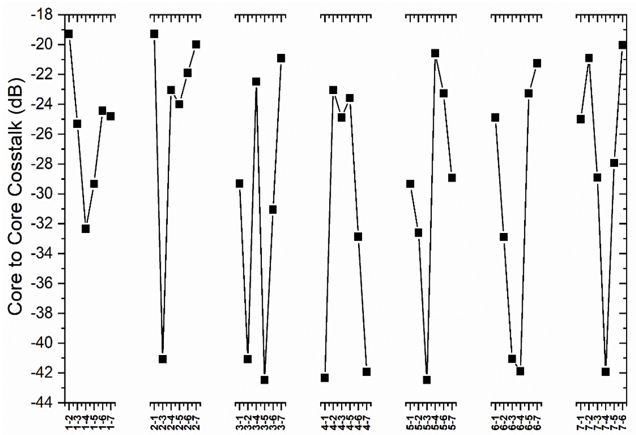


Fig. 5. Interpretation of Crosstalk for 25 µm pitch

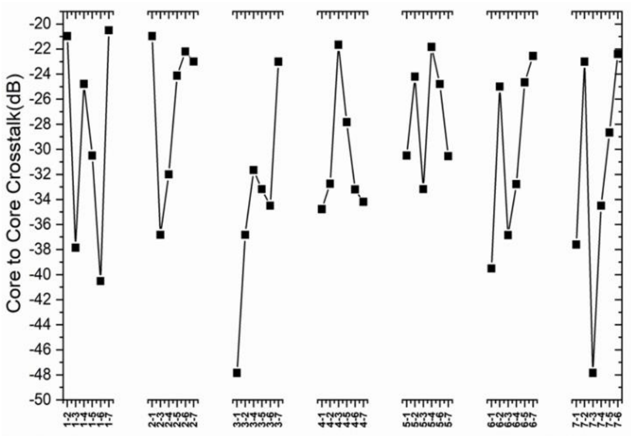


Fig. 6. Interpretation of Crosstalk for 28 μm pitch

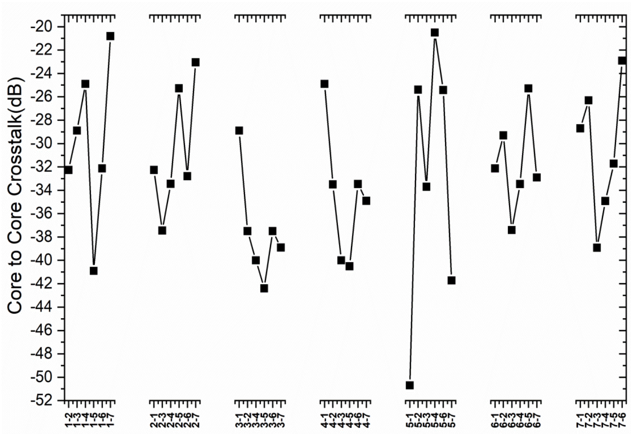


Fig. 7. Interpretation of Crosstalk for 35 μm pitch

5. Conclusion

In this paper, we have analyzed the performance of a novel T-structured 7-core EDFA for three different pitches between the cores. Keeping pace with the development of T-shaped coupler/splitter, this analysis is carried out to contribute to the design and development of optical interconnect application. The authors believe that the findings of this work will be significant in the above-mentioned application. Here, the size of the core and cladding, signal power, pump power, erbium concentration is kept constant. Using all the three different pitches of the core, i.e., 25 μm, 28 μm, and 35 μm, two important analyses, namely performance analysis, and mode analysis, have been conducted and compared with the 7 cores hexagonal structured MC-EDFA. Based on the above simulation for T- structured arrangement of cores in 7-cores EDFA, the results in terms of mode analysis, gain, NF, and XT are presented and discussed elaborately. The results show the prospect of the application of T- structure in MC-EDFA, and the following conclusions can contribute towards improving the design of MC-EDFA.

- Among the three different pitches for T-structured 7-cores EDFA, maximum gain performance (=42.00 dB) is obtained for the radius of 10 μm at 28 μm pitch which is closely followed by the rest of the two pitch.
- An interesting observation obtained from the gain profile for the considered pitches shows that the gain of the T–structured MC-EDFA is not significantly altered by the variation of the pitch. However, its IC-XT seems to be considerably affected. The lowest IC-XT is obtained at 35 μm pitch difference because of less coupling taking place when the cores are wide apart from each other.
- From the comparison of gain analysis and mode analysis for all the three-pitch differences, it has been observed that the difference between gain obtained for the three pitches (25 μm, 28 μm, and 35 μm) is minimal. Along with this, IC-XT is found to be minimum at a pitch of 35 μm.
- It needs to be mentioned that, judicious selection of geometric parameters in the novel T-structured MC-EDFA can deliver gain equivalent to that of the most used hexagonal structure along with an efficient IC-XT profile. Therefore, for the described T-structured MC-EDFA, the authors would like to propose designing it with a core radius (R_{co}) = 10 μm, Λ = 35 μm and using it within the C- band operating wavelength.

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