31. Investigations of Differential Group Delay Behavior in 3-Core Homogeneous Strongly Coupled Multicore Optical Fiber

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ABSTRACT

In this paper, we have investigated the differential group delay (DGD) behavior between different supermodes in 3-core homogeneous strongly coupled multicore fibers (SC-MCFs) for different core refractive index profiles (step index and R.I. dip) and in different possible arrangements (triangular and linear layouts) of cores. Further, the impacts of core pitch (Λ), relative refractive index difference between core and cladding (Δ), and radius (α) on the differential group delay (DGD) between different supermodes have also been analyzed for all the considered configurations of SC-MCFs. The analysis presented has been done using FemSIM simulation platform and MATLAB. It is observed that core configurations and arrangements affect the DGD behavior between different supermodes of SC-MCF. Further, increase in core pitch and radius causes decrease in the DGD values while increase in relative refractive index difference (Δ) results in increase in DGD values. The DGD level is higher in linear layout compared to the triangular layout. However, there exists a particular core pitch below which and certain value of relative refractive index difference (Δ) above which, the DGD value in linear layout is lower than triangular layout. The above analysis will help in the design of MCFs with low value of DGD and its optimization by utilizing fiber design parameters and arrangements of cores.

Index Terms— *Multicore fiber; Homogeneous cores; Supermode; Differential group delay (DGD.*

INTRODUCTION

The existing transmission fiber, i.e., single mode single core fiber (SM-SCF) suffers with the capacity crunch for future ultra-high capacity demand. Therefore, in order to cope with the future capacity demand, space-division multiplexing (SDM) based multicore fiber (MCF) is anticipated to be a potential technology to realize a viable optical network which will be capable to accommodate the several data streams originating from, namely-future 5G communication, machine-to-machine networks, and the internet of things (IoTs) [1]. Further, MCF has been advocated for ultra-high capacity front-haul networks for 5G mobile networks which support several front-haul traffics and further enable the use of analog radio-over-fiber and optical beamforming technology [2].

In SM-SCF, there is only core parameters, i.e., radius and refractive index (R.I.) as a degree of freedom, while, there exists several degree of freedom in terms of core count, core arrangement/layout, core pitch (D) i.e., the separation between the centers of the two cores, cladding diameter (CD), and the outer cladding thickness (OCT) in MCFs. Further, depending upon the core pitch MCFs are of two types, namely-weakly-coupled MCF (WC-MCF) and strongly-coupled multicore fiber (SC-SMF). In WC-MCF, the core pitch is large enough which makes the individual core as a separate waveguide with adequately low mode coupling, mode density, and mode effective area (A_{eff}). Further, low mode effective area results in large nonlinearity and affects the transmission capacity of the fiber. In SC-MCF, cores are placed very close to each other, which causes strong core to core coupling and form supermodes, i.e., superposition of isolated core modes [3]. These supermodes are the eigenmodes of composite structures, i.e., coupled multicore structure [4]. The SC-MCF with n number of cores, exhibits n number of supermodes and among them the fundamental supermode has highest propagation constant (β). In addition to this, supermode structure supports extra degree of freedom especially in terms of core pitch to radius ratio (Λ/a), to manipulate the propagation characteristics and achieve better transmission performance [5]. Therefore, it is important to study the supermodes properties in coupled multicore fibers.

Recently, SC-MCFs with homogeneous cores have been studied to analyze the properties of supermodes using coupled mode theory for different core layouts such as linear array [6], circular [3,7-8] and hexagonal distribution [9-10] in one ring and multiple rings, honeycomb multi-ring arrangement [4], and homogeneous trench-assisted MCF (TA-MCF) in hexagonal one ring structure [11]. The major concern in the long distance transmission of optical signals with high transmission capacity in SC-MCF is the dispersion phenomenon among the different supermodes, i.e., differential group delay (DGD). In applications areas such as, signal processing in 5G (and beyond), fiber-wireless communications, radio-over-fiber transmission and microwave photonics (MWP) signal processing, where the time-delay control and synchronization play the vital role, require a detailed analysis of the group delay of the different cores of the fiber [12]. Several efforts have been made in the analysis of the dispersion properties in SC-MCFs [5, 11-16]. In [5], DGD variation with respect to refractive index difference between core and cladding (Δ), and the core pitch to radius ratio (Λ/a) have been investigated in 3-core strongly-coupled MCF in triangular layout. It is reported that for a particular value of V-number and at a particular wavelength, there exist a value of Λ/a, where the DGD vanishes.

Further, in [16], the variation in the zero DGD wavelength with the variation in separation between the cores in closely spaced two core fibers have been investigated; further, it is reported that by incorporating central refractive index dip in each core, this zero DGD wavelength can also be adjusted by variation in dip parameters. In [13], a compact three core fiber in triangular layout involving refractive index dip in each core have been proposed, and the impacts of R.I. dip parameters on the DGD value have been investigated. Further, it is reported that by proper control of the R.I. dip parameters result in ultra-low DGD over a wide range of wavelength. However, to the author's knowledge, the effect of core arrangements/layouts, core parameters such as radius (α), Δ, and Λ on the DGD among different supermodes in SC-MCFs with homogeneous cores have not been investigated in detailed.

In this paper, we have studied the effect of variations in α , Λ, and Δ on the DGD among different supermodes of 3-core SC-MCFs with homogeneous cores for different R.I. profiles (step index and R.I. dip) and in different possible arrangements (triangular and linear layouts). The rest part of the paper is organized as follows: Section 2 describes the design parameters, schematic designs, and the mode profiles of strongly coupled MCFs in different core layouts (linear and triangular) and R.I. configurations (step index and R.I. dip). The DGD behavior among different supermodes of SC-MCF configurations have been discussed in Section 3 and lastly Section 4 presents the conclusion of the present work.

DESIGN PARAMETERS, SCHEMATIC DESIGNS AND MODE PROFILES OF SC-MCFS

A. DESIGN PARAMETERS

Table 31-1 Design parameters of the 3-Core homogeneous SC-MCFs

Design Parameters	3-Core Homogeneous SC-MCFs				Unit
	Linear	Triangular	Linear R.I. Dip	Triangular R.I. Dip	
A	3.5	3.5	3.5	3.5	μm
n_0	1.444	1.444	1.444	1.444	-
n_1	1.45	1.45	1.45	1.45	-
Λ	$2a$	$2a$	$2a$	$2a$	μm

where, a, n_0, n_1, and Λ are the radius of the core, R.I. of the cladding, R.I. of the core, and core pitch, while, d, and n_d are the diameter of the R.I. dip structure within the core region, and the R.I. of the dip region, respectively.

The values of the fiber design parameters have been taken from [16]. Further, refractive index and the diameter of the R.I. dip region may be expressed as below [13].

$$n_d = \sqrt{pn_1^2 + (1-p)n_0^2} \tag{1}$$

where, $p = 0.5$, and $d = 0.75a$

B. SCHEMATIC DESIGNS AND MODE PROFILES

The schematic designs and the mode profiles of different supermodes in different core layouts of the 3-core homogeneous SC-MCFs have been shown in Figs. (31-1)-(31-4).

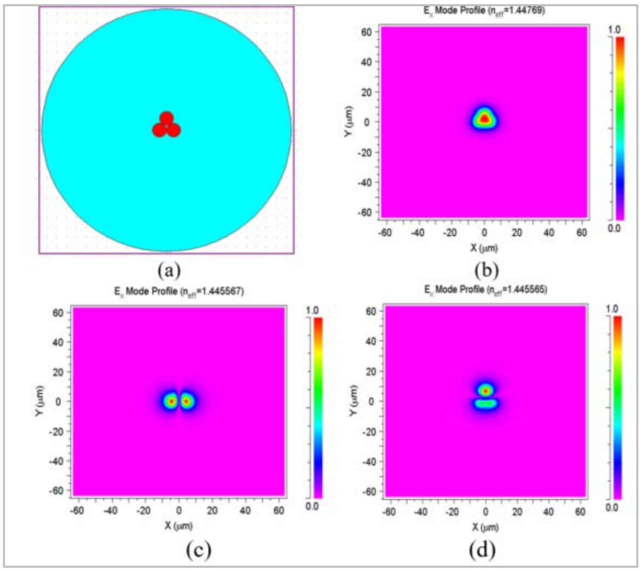

Figure 31-1 Core triangular homogeneous strongly coupled MCF (a) Schematic design, and mode profiles of (b) fundamental and (c), (d) higher order supermodes

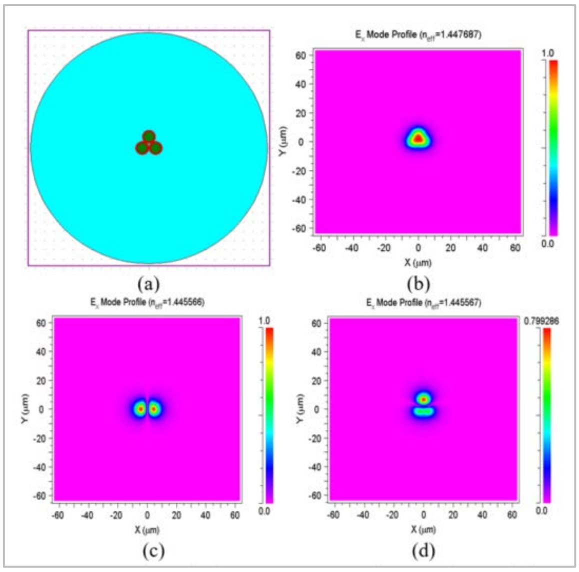

Figure 31-2 Core triangular homogeneous R.I. dip strongly coupled MCF (a) Schematic design, mode profiles of (b) fundamental and (c), (d) higher order supermodes

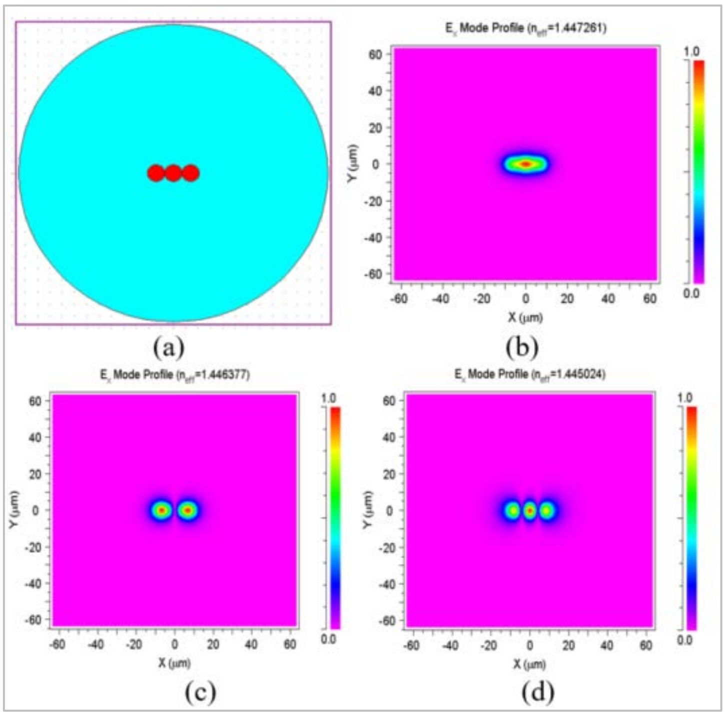

Figure 31-3 Core linear homogeneous strongly coupled MCF (a) Schematic design, mode profiles of (b) fundamental and (c), (d) higher order supermodes

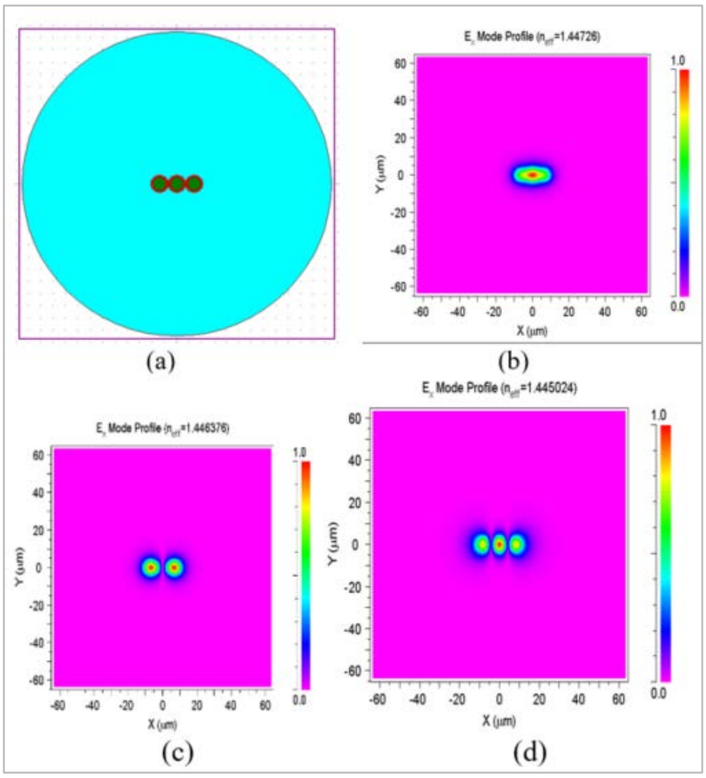

Figure 31-4 S-Core linear homogeneous R.I. dip strongly coupled MCF (a) Schematic design, mode profiles of (b) fundamental and (c), (d) higher order supermodes

RESULTS AND DISCUSSION

The differential group delay (*DGD*) between any two supermodes of coupled MCFs can be obtained by [13]

$$DGD = \frac{1}{c}\left[\Delta n_{eff} - \lambda \frac{d(\Delta n_{eff})}{d\lambda}\right] \tag{2}$$

where, *c* is the speed of light in vacuum and Δn_{eff} is the effective refractive index difference between any two supermodes. In the present analysis, we have calculated the values of *DGD* among different supermodes of various configurations of coupled MCFs using Eqn. (2) and plotted in the Figs. (31-5) - (31-8). The values of n_{eff} for different supermodes have been calculated using FemSIM simulation platform.

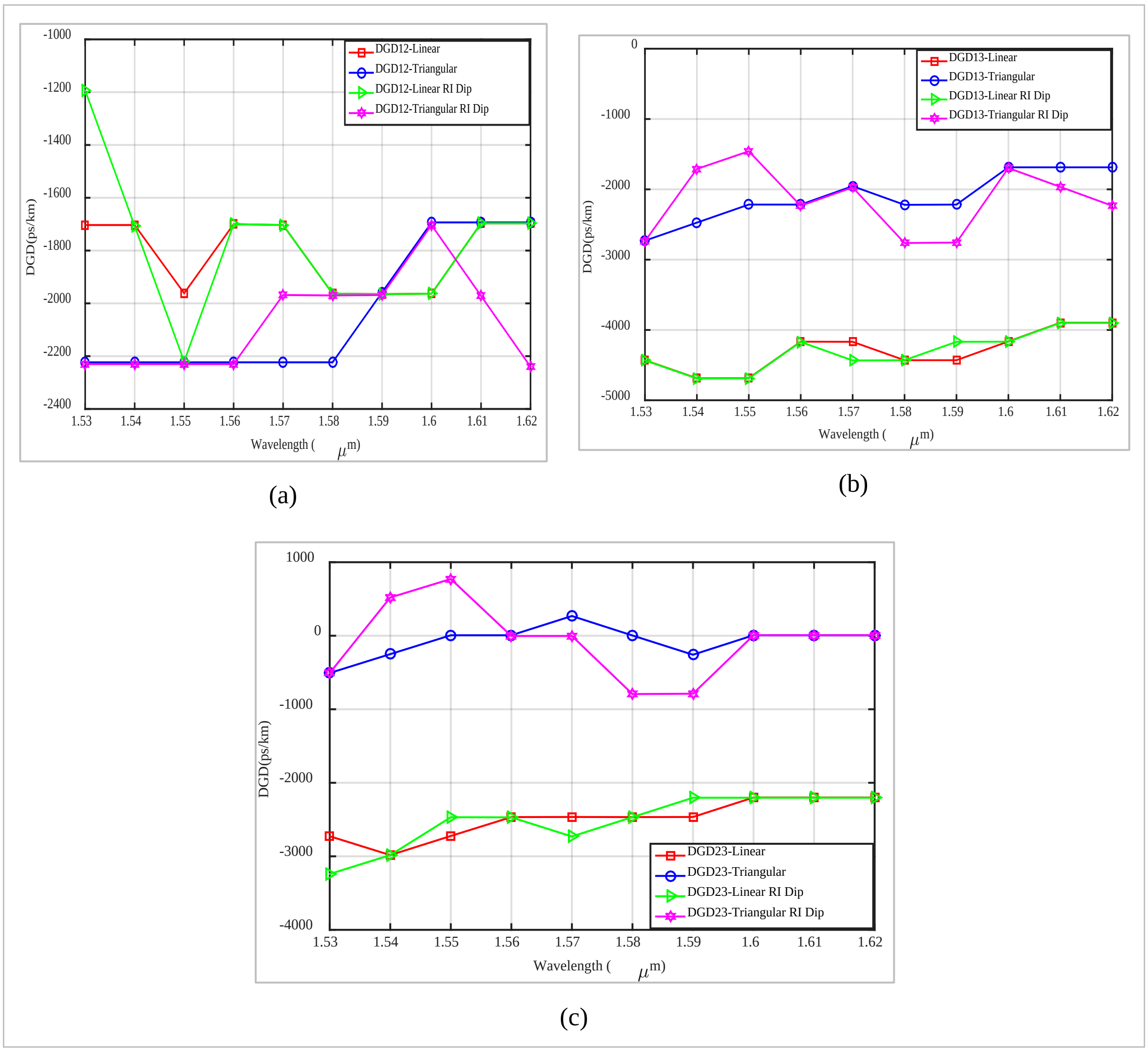

Figure 31-5 Wavelength dependent DGD variations in 3-core strongly coupled MCFs with homogeneous cores for different core layouts (a) DGD_{12} (b) DGD_{13} (c) DGD_{23}

Figures 31-5(a)-(c) show the wavelength dependent *DGD* variations among different supermodes of 3-core SC-MCFs. In 3-core SC-MCFs there are three supermodes, among them the supermode with highest propagation constant (β) is called as fundamental supermodes and the other supermodes are called as higher order supermodes. The supermode numbers (1, 2, and 3) have been assigned in decreasing order of their propagation constant. The different *DGDs* namely- DGD_{12},DGD_{13}, and DGD_{23} are the *DGDs* between supermodes 1 and 2, supermodes 1 and 3, and supermodes 2 and 3, respectively. The maximum value of the *DGD*, i.e.,$|DGD|_{max}$ over the considered wavelength range in linear and triangular layouts are 4690 ps/km and 2737 ps/km respectively. Therefore, the core layout has significant impact on the *DGD* levels. Further, incorporating R.I. dip structures in the core regions of linear and triangular layouts have significant impact on the *DGD* levels, and they exhibits relatively higher value of $|DGD|_{max}$ compared to their without R.I. dip structures over the considered wavelength region.

In Figs. (31-6)-(31-8), due to degeneracy in propagation constants (having similar propagation constant values) of higher order supermodes (supermodes 2 and 3) in triangular layout, *DGD* between supermodes 2 and 3 is nearly zero.

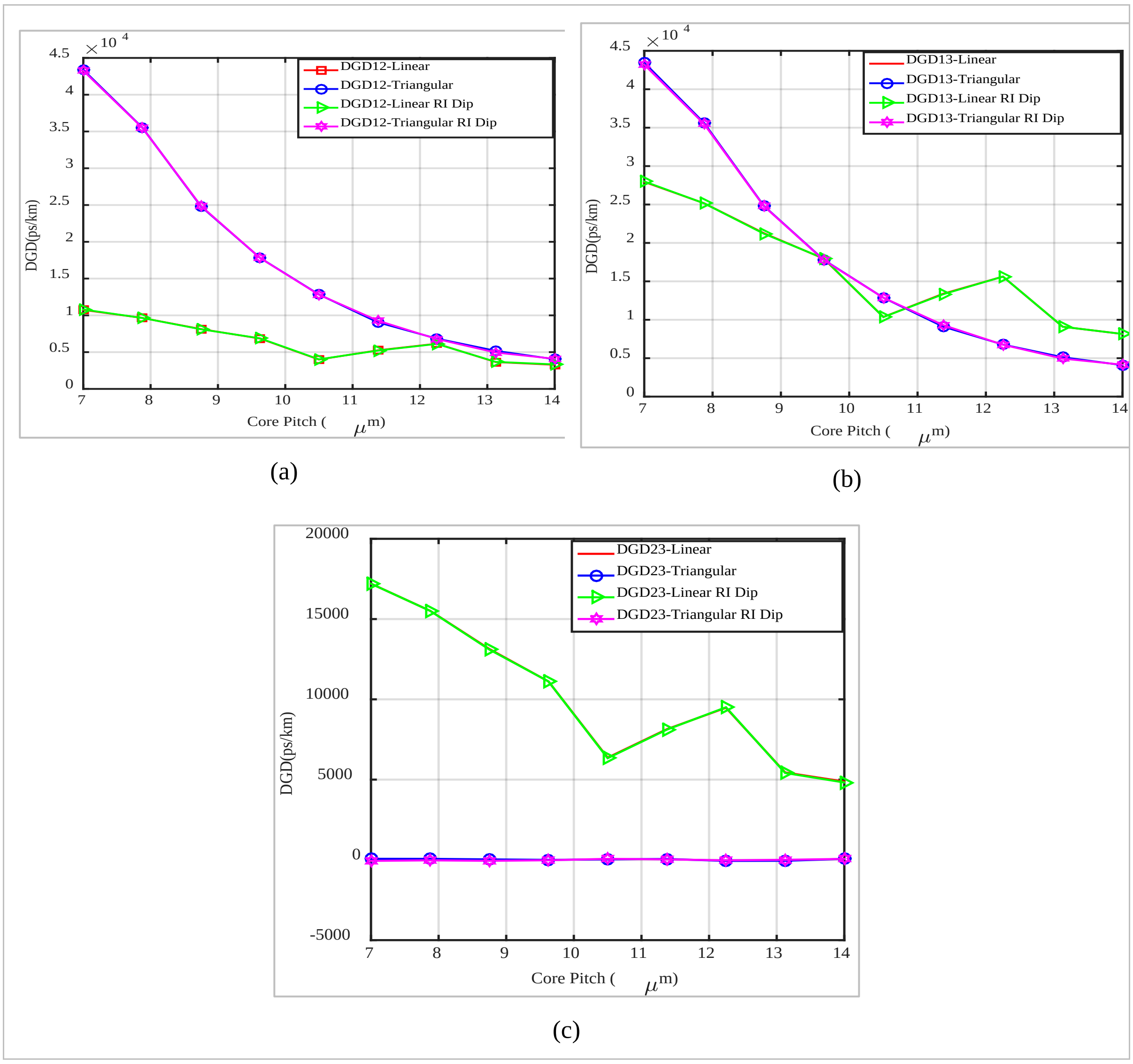

Figure 31-6 Core pitch dependent DGD variations in 3-core strongly coupled MCFs with homogeneous cores for different core layouts (a) DGD_{12} (b) DGD_{13} (c) DGD_{23}

While, linear layouts have different values of propagation constants for the different supermodes, therefore, they have different *DGD* values. This is mainly due to the symmetrical mode coupling in all cores of triangular layout, as each core in triangular layout has same number of surrounding cores; while in linear layout, the cores at the extreme end have only one neighboring core and intermediate cores have more than one neighboring cores.

In Fig. 31-6, core pitch has different impacts on the *DGD* levels in linear and triangular layouts due to the different arrangements of cores. Initially for smaller core pitch values, the *DGD* value is higher in triangular layout compared to linear layout. While, there exits certain core pitch after which *DGD* level in linear layout is higher compared to the triangular layout. However, the rate of decrease in *DGD* levels is higher in triangular layout compared to the linear layout. In Fig. 31-7, DGD values in all layouts decreases with the increase in core radius. Further, the value of *DGD* is higher in linear core layout compared to the triangular layout. The maximum value of the *DGD* i.e., $|DGD|_{max}$in linear and triangular layouts are 13,720 ps/km and 12650 ps/km, respectively. From Fig. 31-8, it is observed that increase in relative refractive index difference (Δ) results in increase in *DGD* values for all configurations of SC-MCFs. Although, the value of $|DGD|_{max}$ occurs in linear layout, but after a certain value of Δ, $|DGD|_{max}$value is lower in linear layout compared to triangular layout. Moreover, the rate of increase in $|DGD|_{max}$ levels is higher in linear layout compared to the triangular layout. On the other hand, incorporating R.I. dip structures in the two core layouts have no significant impact on the *DGD* levels compared to the without R.I. dip structures of respective layouts.

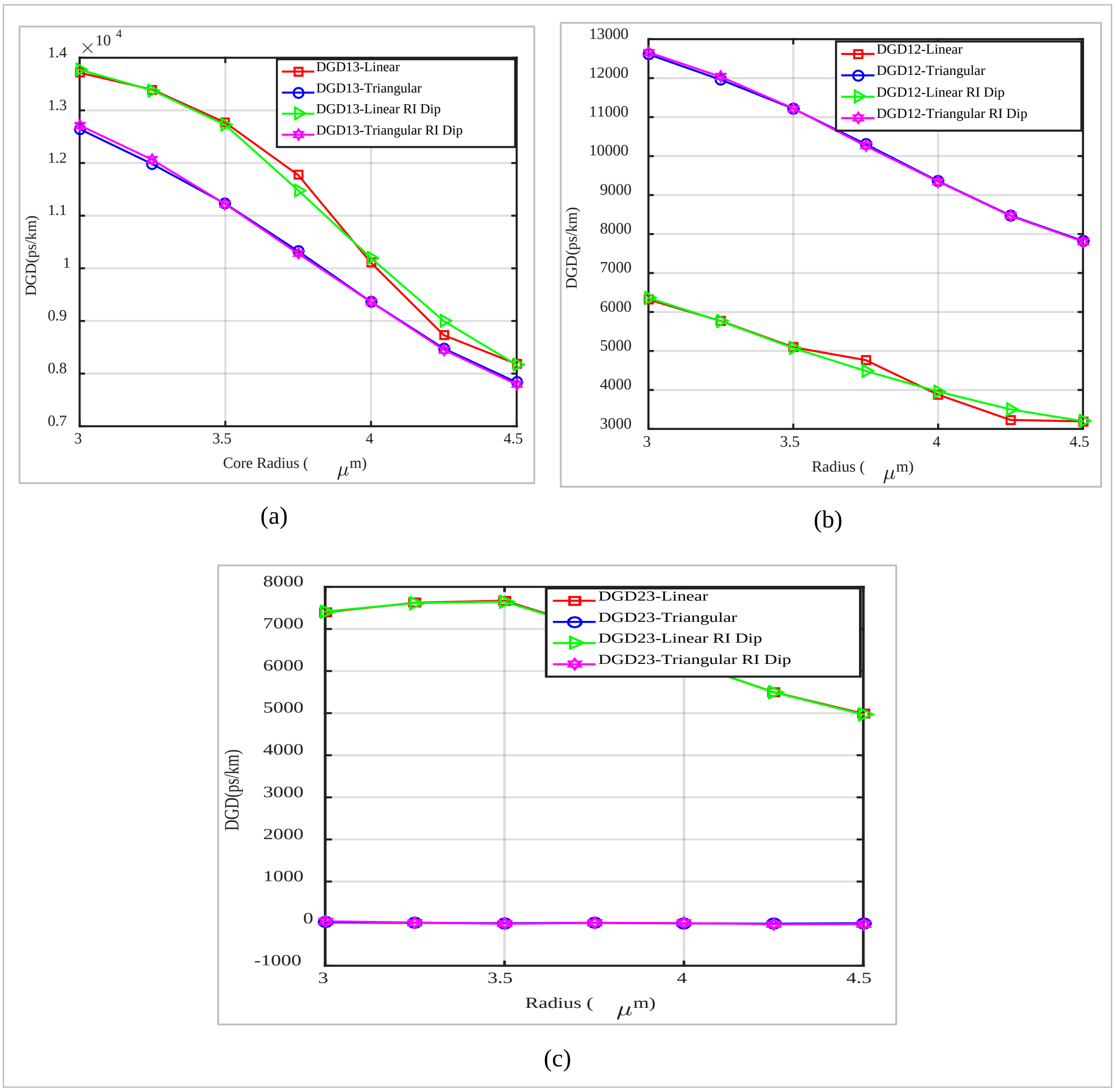

Figure 31-7 Core radius dependent DGD variations in 3-core strongly coupled MCFs with homogeneous cores for different core layouts (a) DGD_{12} (b) DGD_{13} (c) DGD_{23}.

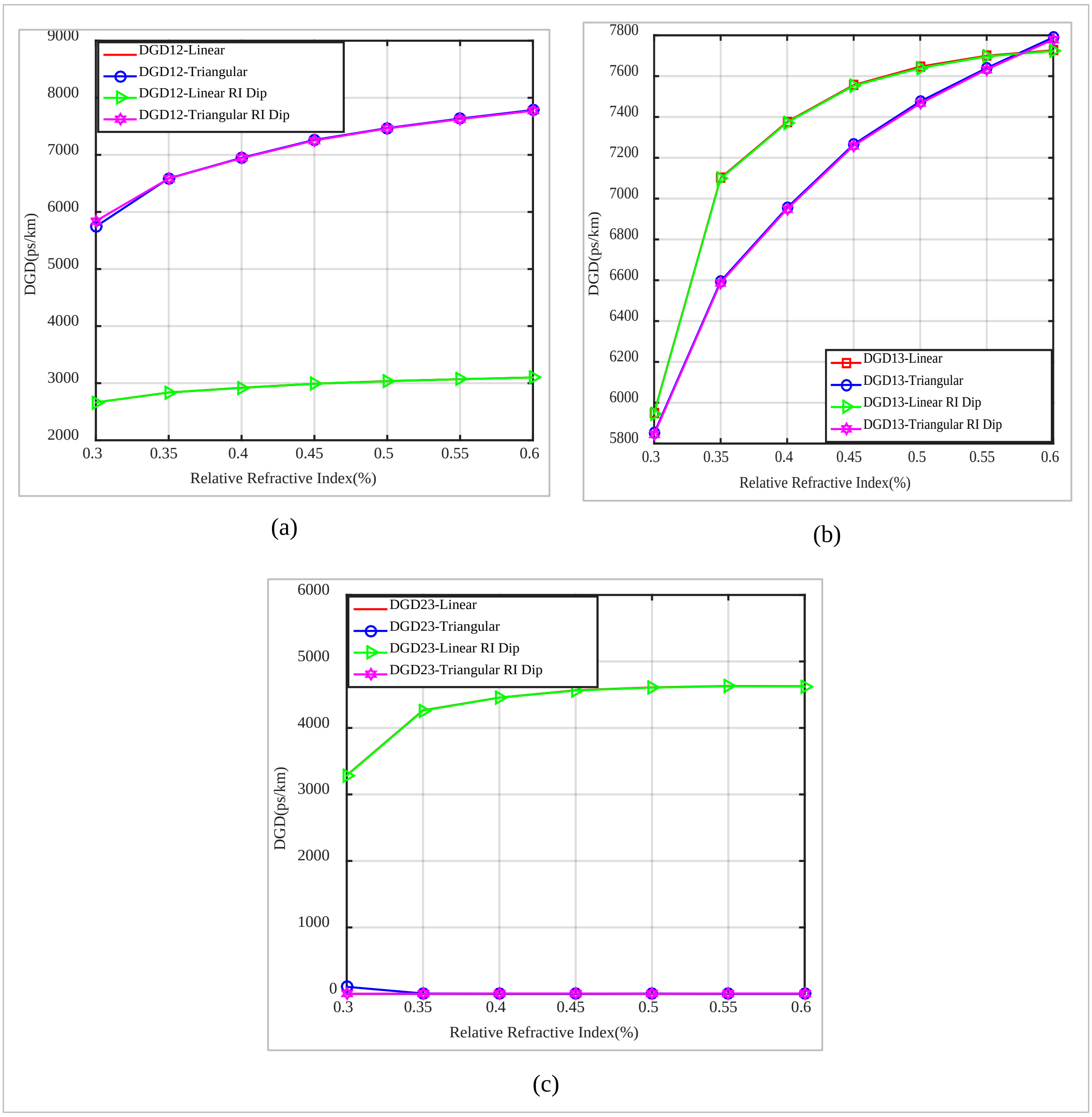

Figure 31-8 Relative refractive index difference dependent DGD variations in 3-core strongly coupled MCFs with homogeneous cores for different core layouts (a) DGD_{12} (b) DGD_{13} (c) DGD_{23}.

CONCLUSION

In the present analysis, impacts of core pitch (Λ), core radius (α), and relative refractive index difference between core and cladding (Δ) on the differential group delay (DGD) behavior among different supermodes of 3-core homogeneous SC-MCF layouts have done using FemSIM simulation platform and Matlab. The cores of MCFs under consideration have been arranged in linear and triangular layouts. It is observed that core configurations and arrangements affect DGD behavior between different supermodes of SC-MCF. Further, increase in core radius and pitch causes decrease in the DGD values while increase in relative refractive index difference (Δ) results in increase in DGD values. However, there exists a particular core pitch below which and certain value of relative refractive index difference (Δ) above which the DGD value in linear layout is lower than triangular layout. The above analysis will help in the design of MCFs with low value of DGD and its optimization by utilizing fiber design parameters and arrangements of cores.

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