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Performance of Fiber Raman Amplifier due to Change in Refractive Index of Second Core of Dual Core Fiber Raman Amplifier

Abstract: We vary the refractive index of second core of dual concentric cores of a single mode Fiber Raman Amplifier (FRA), having a step profile. Based on well known scalar analysis, we study crucially the effects of this variation on the performance characteristics of FRA for the first time. For practically important frequency shift band of 20 cm^{-1} to 700 cm^{-1}, our interesting observation is that values of refractive indices in a certain higher range show better flattening of effective raman gain in comparison to those in lower range with single pump; side by side, larger negative coefficient of dispersion is achieved in the operating range of wavelength with increase of refractive indices keeping the outer core radius, core gap radius and refractive index of the first core fixed. These promising criteria should attract the attention of system designers engaged in fabrication of FRA.

Keywords: Fiber Raman Amplifier, effective raman gain, effective area, dispersion coefficient

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1 Introduction

Today single mode Fiber Raman Amplifier (FRA), constructed by dual concentric cores meets up the high speed need of Internet traffic in WDM and DWDM because attenuated signals are optically amplified by the fiber based amplifier [1]. Here amplification of signals does not require any doping in narrow region of fiber core as in Erbium doped fiber amplifiers (EDFA). In case of FRA, Stimulated Raman Scattering (SRS), a nonlinear optical phenomenon, is applied and the photon energy is utilised from one optical domain of higher frequency, known as a pump, to another domain at lower frequencies, known as the signal, for amplification [2]. Also the gain spectrum of FRA depends solely on the pump wavelength; hence it becomes simpler and easier to access inaccessible bands like S-band by EDFA's [3]. Thus FRA which can provide 3 dB bandwidth of 90 to 100 nm, has emerged as the potential solution to be used as an optical amplifier. Since the effective raman gain coefficient [4], which is the ratio of raman gain coefficient and effective area, assumes almost a uniform value with frequency shift in the said wavelength band, there is no restriction of selecting signal frequency band in FRA in which only we have to choose proper pump wavelength. We concentrate signals of wavelength to be amplified around a particular value in S-band.

Very recently, comparative studies of performance criteria of FRA with various refractive index profile distributions in core including step, parabolic, triangular [5] ones have received keen attention in relation to the variation of the effective raman gain, effective area and dispersion coefficient with frequency shift keeping the phase matching condition fixed. Similar work has also included trapezoidal index profiles of practical interest [6]. Also investigation on FRA involving photonic crystal structures has started attracting interest in the context of signal amplification and dispersion compensation [7].

In this paper, our aim is to investigate whether there is a suitable structural parameter for a step FRA in order to achieve better gain flattening w.r.t. a single pump corresponding to particular wavelength. We focus our attention to concentric step profile for its conventionally accepted use and variation of the refractive index of second core, keeping the distance of separation between first and second cores in the profile, refractive index of first core and other structural parameters remaining constant. Our encouraging observation is that values of refractive index of second core in a certain higher range show better flattening of effective raman gain in comparison to those in lower range with single pump. Thus structures with higher refractive index will exhibit flattening with single pump whereas structures with the lower ranging refractive index should show gain flattening with multiple pumps requiring cost based technological intricacies. With the above proposal, it is therefore possible to realise a suitable FRA in the S band operation. Side by side, another important aspect is revealed that larger negative dispersion coefficient is also achieved in the said wavelength band for higher range of refractive index as well as minimum dispersion coefficient also shifting towards lower value of wavelength. Advantageously one can, then, choose FRA of certain length with the particular value of refractive index and determine the value of dispersion and attach to the total link and make the proper amplification and minimise dispersion [8]. In subsequent sections we present our analysis for computation and simulation together with results and discussions.

2 Modelling and analysis

2.1 Profile structure

Our proposed optical fiber, shown in Fig. 1, has a coaxial refractive index profile with inner and outer cores. We confine our attention to a single mode regime with profile distribution as

$$n^2(r) = \begin{cases} n_1^2\left[1-\Delta_1 f(\rho)\right] & \text{for} \quad 0 \le \rho \le 1 \\ n_3^2 & \text{for} \quad 1 \le \rho \le b \\ n_2^2 & \text{for} \quad b \le \rho \le c \,(\text{varying}) \\ n_3^2 & \text{for} \quad c \le \rho \end{cases} \tag{1}$$

where n_1, n_2 and n_3 are refractive indices of the inner core, outer core and cladding; $\Delta_1 = (n_1^2 - n_3^2)/n_1^2$, $\rho = r/a$; r is the radial distance and a is first core radius; b is the core gap radius; $(c-b)$ is outer core radius region. The profile function, $f(\rho)$ is given as $f(\rho)=\rho^q$; here q tends to ∞ for step

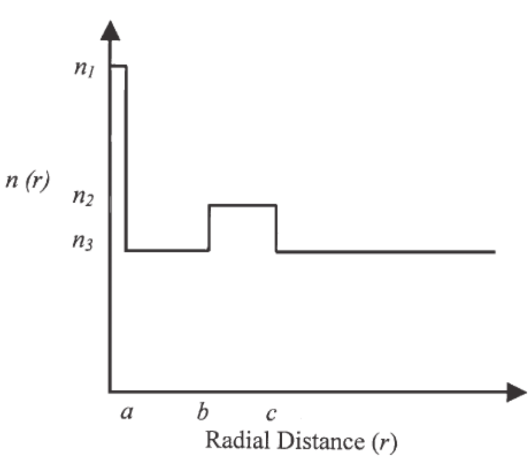

Fig. 1: Refrative index vs. Radial distance to indicate the profile.

profile. The profile is sampled into small units of rectangle to compute the field distribution in each rectangular segment and effective index of refraction (n_{eff}). The total field is the algebraic sum of all such segment based fields [5], [9]. The effective refractive index bears the relation with propagation constant and wave number,

$$\beta^2 = k^2 n_{eff}^2 \tag{2}$$

where β is the propagation constant and $k = 2\pi/\lambda$ is the wave vector in the dielectric medium of optical fibre with $k_0 = 2\pi/\lambda_0$ being the free space wave vector whereas λ and λ_0 being the wavelengths in the medium and free space.

2.2 Raman gain model

For small signal regime, one can ignore the pump depletion due to SRS. The variations of pump power (P_p) with pump wavelength λ_p and signal power (P_s) with signal wavelength λ_s are described by the following couple mode equation [3], [5]

$$\left.\begin{aligned} dP_p/dz &= -\alpha_p P_P, \\ dP_s/dz &= \gamma_R P_P P_S - \alpha_s P_s \end{aligned}\right\} \tag{3}$$

where α_p and α_s are attenuation coefficients at pump and signal wavelength, γ_R being effective Raman gain coefficient, given as [2], [6]

$$\gamma_R = \frac{g_R(\upsilon)}{A_{eff}} \tag{4}$$

where $g_R(\upsilon)$ is Raman gain coefficient; A_{eff} is the effective area, defined in terms of pump and signal modal fields as

$$A_{eff} = 2\pi \frac{\int \psi_p^2 r dr \int \psi_s^2 r dr}{\int \psi_p^2 \psi_s^2 r dr} \tag{5}$$

and is computed from the overlap integral of two modal fields [6]. In the FRA structure, the effective area A_{eff} varies in such a way that the effective Raman gain coefficient becomes constant over the 90 nm bandwidth as the Raman gain decreases sharply and side by side the effective area A_{eff} increases in accordance with the decrease, eventually maintaining gain flattening.

The Raman gain coefficient is expressed by the following equation [2], [3]:

$$g_R(x_{GeO_2},\upsilon) = \frac{n_2^2}{n_1^2}\left[g_R(SiO_2,\upsilon) + C(\upsilon) x_{GeO_2} g_{Rp}(SiO_2,\upsilon)\frac{\lambda_s^3}{\lambda_{sPeak}^3}.\right] \tag{6}$$

where g_{R_p} is the peak Raman gain coefficient, x_{Geo_2} is the Germanium concentration; $C(\upsilon)$ is the linear regression coefficient; $_{sPeak}$ is the signal wavelength at which the peak Raman gain is obtained.

2.3 Dispersion coefficient

The dispersion coefficient meaning group velocity dispersion is given as

$$D(\lambda)=-\frac{\lambda}{c}\frac{d^2n_{eff}}{d\lambda^2} \tag{7}$$

where c is the velocity of light.

2.4 Scalar wave equation

In order to find pump and signal fields and effective refractive indices, we use the following scalar wave equation under weakly guiding approximation [8]:

$$\frac{\partial^2\psi}{\partial r^2}+\frac{1}{r}\frac{\partial\psi}{\partial r}+\left[\omega^2\varepsilon(r)\mu_0-\beta^2\right]\psi(r)=0 \tag{8}$$

where $\varepsilon(r)$ is dielectric permittivity of optical fiber at radial distance r, μ_0 is free space permeability of the medium. The modal field is expressed by Bessel and modified Bessel equation as

$$\psi(r)=\begin{cases}AJ_0(\kappa r)+BY_0(\kappa r) & \text{for} \quad n(r)>n_{eff} \quad (9)\\ CI_0(\omega r)+DK_0(\omega r) & \text{for} \quad n(r)<n_{eff} \quad (10)\end{cases}$$

with κ^2 and ω^2 are given as

$$\kappa^2=k_0^2\left[n^2(r)-n_{eff}^2\right] \tag{11}$$

$$\omega^2=k_0^2\left[n_{neff}^2-n^2(r)\right] \tag{12}$$

The effective refractive index (η_{eff}), constants A, B, C and D and the field, $\psi(r)$ in the above equations are evaluated by matrix method [4], [9] where we partition the whole index profile of the proposed optical fiber into smaller rectangular segments and by apply boundary condition of continuity with the field $\psi(r_i)$ and $\frac{\partial\psi(r_i)}{\partial r}$ for ith and $(i+1)$th segments. In the next section, we present the results and discussions based on our simulation work using MATLAB 7.0 and involving the above theoretical framework.

3 Results and discussion

3.1 Profile and phase matched wavelength

With reference to Fig. 1, the refractive index, n_1 of the first core is taken 1.47299, refractive index of second core n_2 which is varied from 1.44801 to 1.44871 at step of 0.0001 in the first set of data and from 1.44871 to 1.44881 at step of 0.00001 for second set of data; the refractive index of the cladding, n_3 is 1.444388 at 1.55 µm of pure silica. The core gap radius, b is 9.0 µm., first core radius, a is 1 µm and second core width, $c-b$ and are kept fixed at 7.32 µm all through the simulation. The parameters Δ_1 and $\Delta_2=(n_2^2-n_3^2)/n_2^2$ are calculated and presented with other data in Table 1.

Here, we find the fundamental modal field (ψ) and effective refractive index (n_{eff}) for the structure corresponding to the wavelength range 1.46 to 1.75 µm for a particular value of n_2, by solving scalar wave equation and solution thereof in (9) and (10) using matrix method. Likewise, we repeat the above process to find effective indices and modal field for different values of n_2 ranging from 1.44801 to 1.44871 at step of 0.0001. They are given in the Fig. 2a to Fig. 2e. Such plots, (n_{eff} vs. wavelength (λ) in µm are depicted for different values of n_2 as 1.44801 and 1.44871 where the values of Phase Matched Wavelength (PMW) coming as represented in the Table 2. In all the figures, the two dotted lines, at the top and at the bottom, represent the effective indices for two LP_{01} and LP_{02} super-modes respectively at different wavelengths. We find the similar nature of plot for different values of n_2 and see that PMW lies within 1.497 µm and 1.59 µm and does not change appreciably with n_2. Consequently, the choice of pump wavelength is kept at 1.465 µm much below the PMW.

Core 1 & 2	**Δ_1 (%)**	**Δ_2 (%)**	**n_2 (refractive index of second core)**	**a (µm)**	**$c-b$ (µm)**
Step	3.0	0.250	1.44801	1	7.32
		0.257	1.44811		
		0.264	1.44821		
		0.271	1.44831		
		0.277	1.44841		
		0.284	1.44851		
		0.29	1.44861		
		0.29	1.44871		

Table 1: Profile Structure.

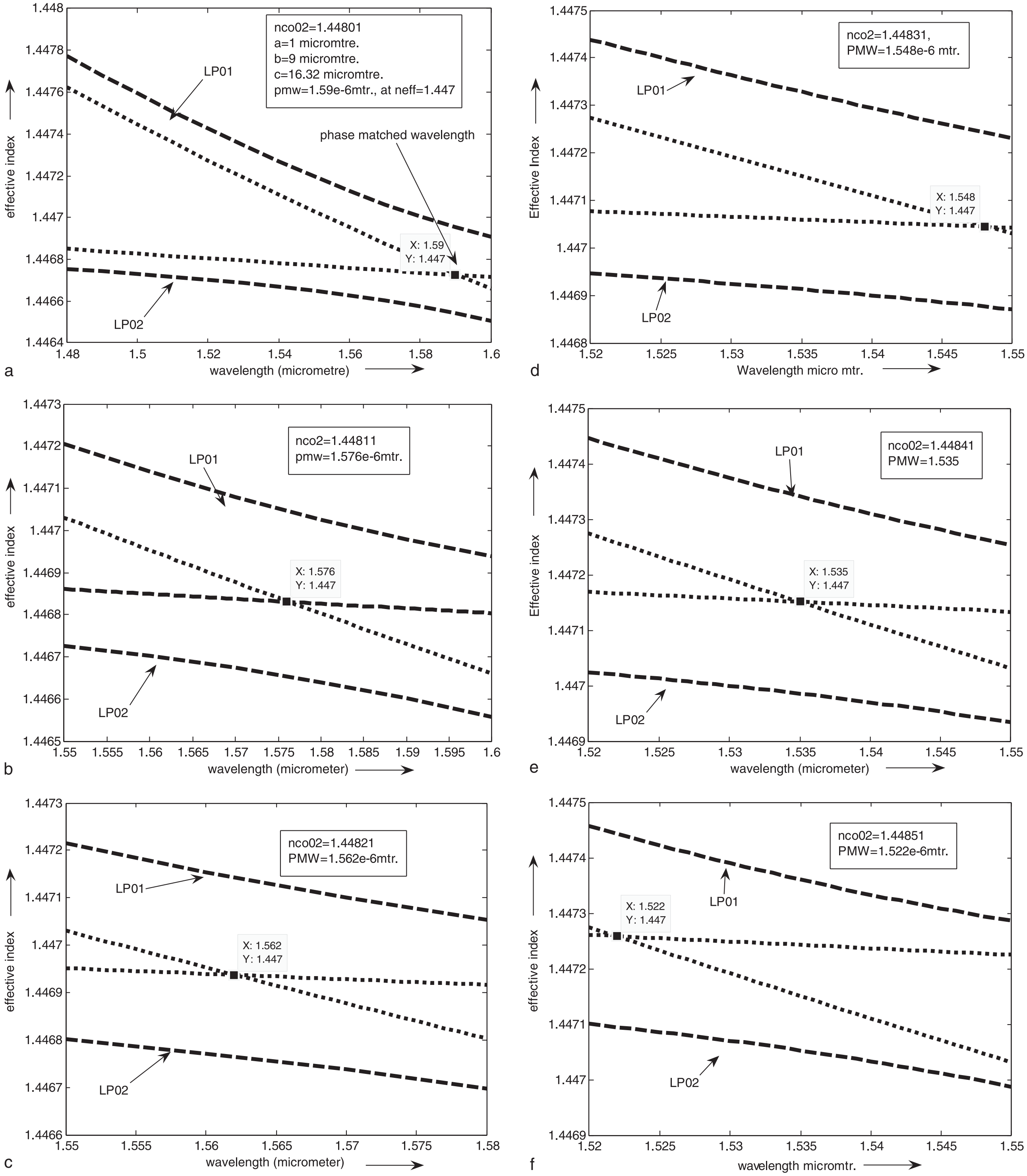

Fig. 2a to 2f: Effective index (η_{eff}) vs. wavelength (μm). Two super modes LP_{01} and LP_{02} and phase matched wavelength are shown for different values of refractive indices of second core of two concentric core step profile.

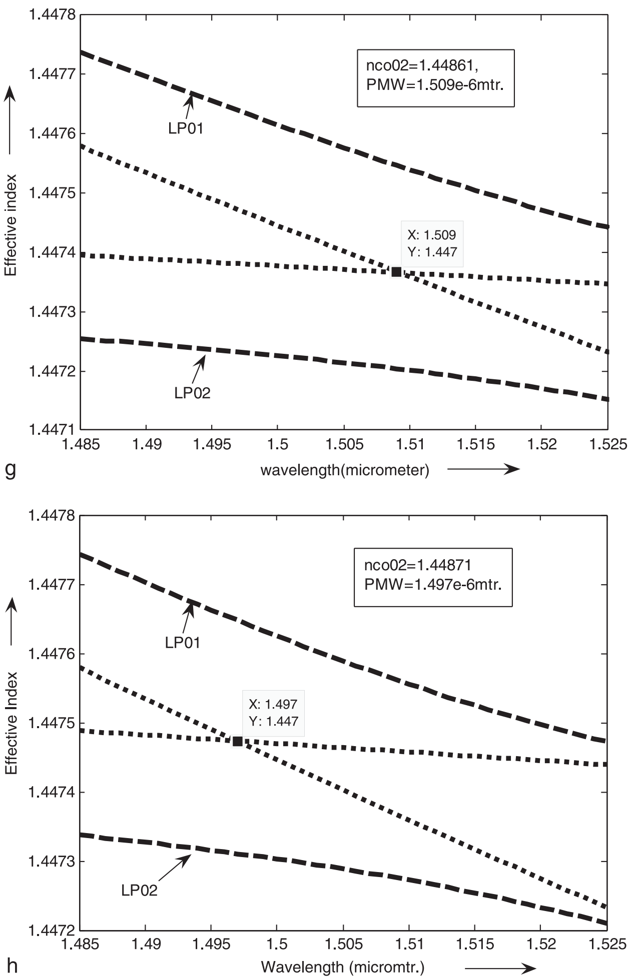

Fig. 2g to 2h: (Cont.)

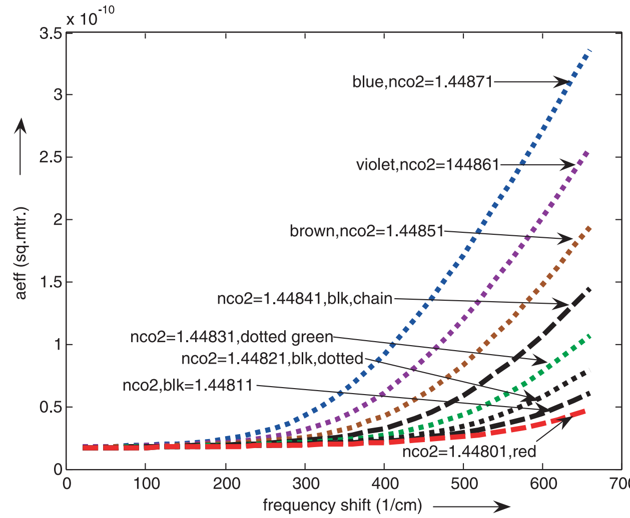

Fig. 3: Effective area (sq.m.) vs. frequency shift (cm^{-1}) for different values of refractive indices of second core without changing other profile parameters.

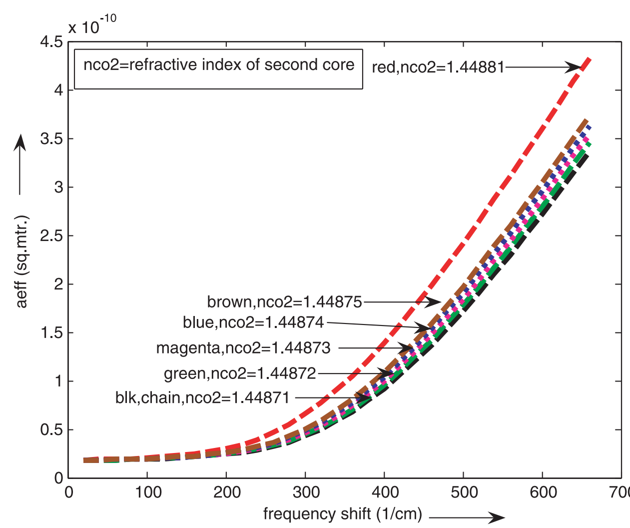

Fig. 4: Effective area (sq.m.) vs. frequency shift (cm^{-1}) for different values of refractive indices (second set) of second core of optical fiber keeping other profile parameter fixed.

3.2 Effective area and effective Raman gain

The values of effective area are obtained by applying the equation (5) for different frequency shifts and are plotted as the curve shown in Fig. 3 and Fig. 4, where effective area is found increasing with increase in n_2 and the different

Sl no.	n_2-value	Min. value of dispersion coefficient (ps/(nm.km))	Min. dispersion wavelength (μm)	Phase matched wavelength (μm)
1.	1.44801	−340.1	1.60	1.597
2.	1.44811	−368.6	1.59	1.576
3.	1.44821	−400.1	1.58	1.562
4.	1.44831	−434.0	1.57	1.549
5.	1.44841	−471.7	1.56	1.535
6.	1.44851	−512.4	1.55	1.522
7.	1.44861	−559.4	1.535	1.509
8.	1.44871	−603.4	1.53	1.497
9.	1.44881	−670.3	1.515	1.485

Table 2: Dispersion coefficient for higher core gap radius.

values of n_2 from 1.44801 to 1.44871 in Fig. 3 for one set and 1.44872 to 1.44881 in Fig. 4 for another set.

The Raman gain is obtained from the formula given by equation (6) for a step profile distributed amplifier. For our proposed amplifier we choose a single pump system at wavelength 1.465 μm much below the PMW (1.517 μm). The frequency corresponding to peak Raman gain coefficient is found at 13.2 THz and gain is $1.046 \cdot 10^{-13}$ m/W at λ_p equals to 1.465 μm [3], [4]. The operating region of wavelength is chosen for frequency shift 20 cm^{-1} to 700 cm^{-1} and the value of x_{GeO_2} is taken as 19.83. The effective Raman gain coefficient vs. frequency shift is plotted and presented in the Fig. 5 and Fig. 6 for two sets of values of n_2's.

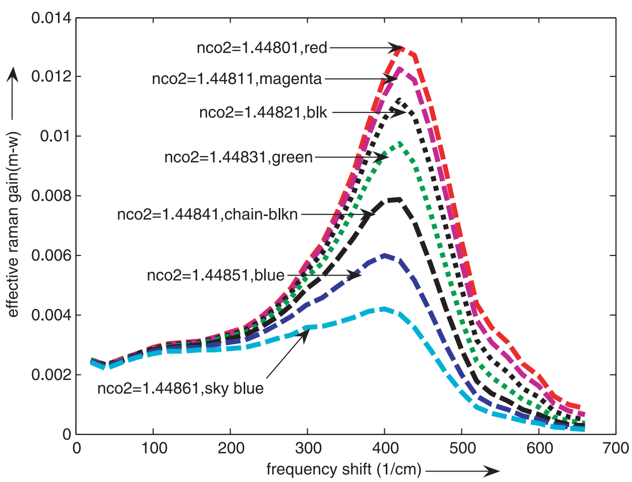

Fig. 5: Effective Raman gain ((m-W)$^{-1}$) vs. frequency shift (cm^{-1}) for different values of refractive index of second core of optical fiber with second set of data.

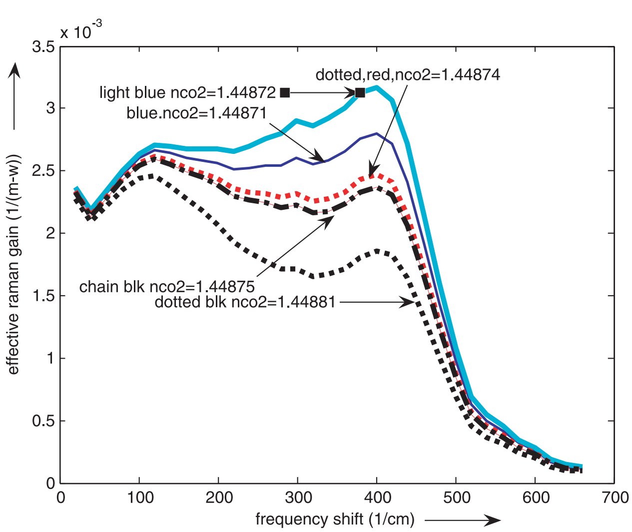

Fig. 6: Effective Raman gain ((m-W)$^{-1}$) vs. frequency shift (cm^{-1}) for different values of refractive index (second set) of the scond core.

In the lower set of values of n_2, we find an overshoot occurring in the value of effective gain near the frequency shift of 450 cm^{-1}. This overshoot in the values of effective raman gain is much reduced with other set of values of n_2's as we increase n_2, shown in the Fig. 6. When signal wavelengths are below 1.517 μm, the pump and signal is tightly confined to the inner core for which we get much overlapping between the two, pump and signal, resulting in smaller effective area, A_{eff}. As the signal wavelength approaches towards PMW, the fractional power spreads to the outer core and overlapping between pump and signal is less, resulting in larger effective area, A_{eff}. However although we get better flattening of effective raman gain in higher range of n_2 without any appreciable overshooting of values, the highest value of effective raman gain coefficient is more in case of lower range of n_2 for $\Delta\upsilon \approx 400$ cm^{-1}. Therefore whereas one can get better flattening by using a high power single pump at a suitable wavelength for FRA structure corresponding to higher range of n_2, one should have to use multiple pumps for such structure relating to lower range of n_2.

3.3 Dispersion coefficient

Now although γ_R is more crucial in studies on FRA, one cannot avoid the importance of wide knowledge of dispersion coefficient in choosing a dispersion-compensated module. Fig. 7 shows the plot of dispersion coefficient vs. wavelength for n_2 values ranging from 1.44801 to 1.44861. Similarly, the Fig. 8 shows the same variation for the other range of n_2 from 1.44871 to 1.44881 for three values to get

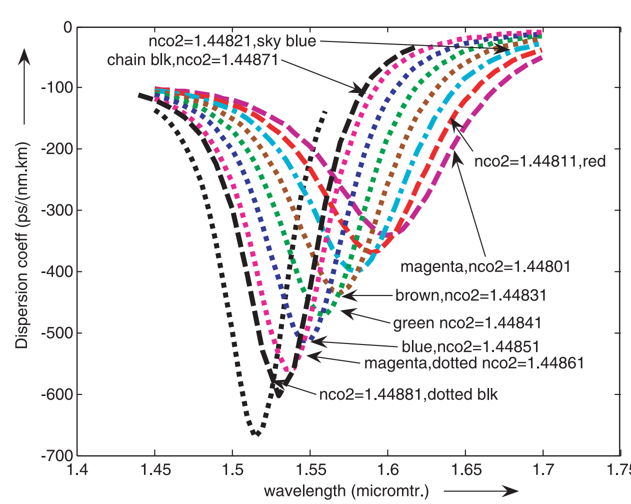

Fig. 7: Coefficient of Dispersion (ps/(nm.km)) vs wavelength (μm) for (first set of data) the values of refractive index of second core.

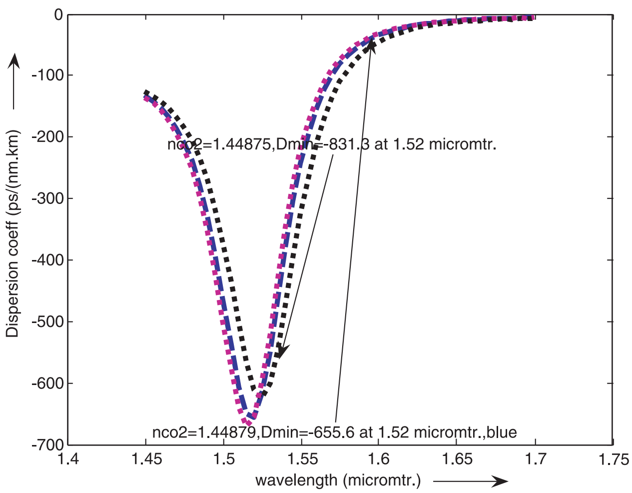

Fig. 8: Coefficient of Dispersion(ps/(nm.km)) vs wavelength for different values of refractive index of second core (second set of data)

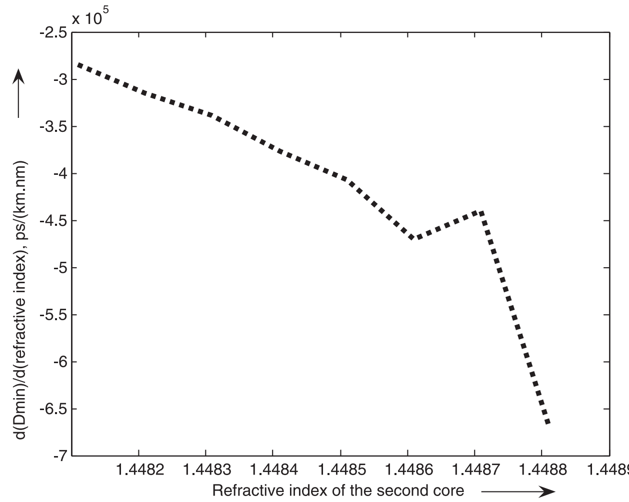

Fig. 10: Phase matched wavelength vs. second core refractive indices.

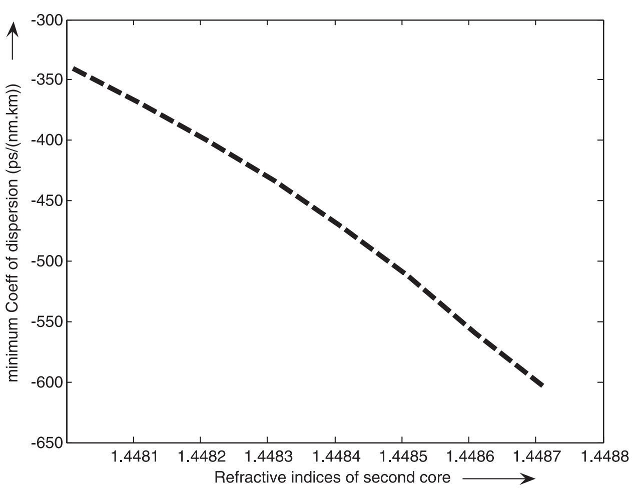

Fig. 9: Minimum dispersion coefficient, D_{min} ((ps/(nm.km)) vs. refractive index of second core.

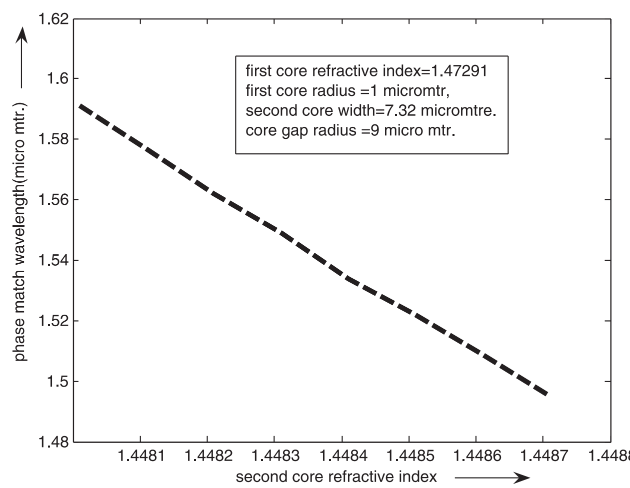

Fig. 11: Rate of change of minimum dispersion coeff w.r.t. change of refractive index vs. refractive index.

an idea how the change in performance of effective Raman gain occurs. The plot shows that we must restrict the value of refractive index from 1.44871 to 1.44881 to operate the optical fiber to produce the effective Raman gain uniform with single pump. The minimum coefficient of dispersion, D_{min} goes down below towards more minimum, with the increase of values of n_2. The minimum dispersion coefficient are shown in the Table 2 for such range of values of n_2.

We present the graphical variation of minimum dispersion (D_{min}) coefficient with different values of n_2 in the Fig. 9. It is found that the curve goes down with negative gradient and almost uniformly. Subsequently we plotted the Fig. 10 to show the rate of change of minimum dispersion coefficient w.r.t change in refractive index of second core where it is observed that the curve is almost linearly falling up to $n_2 = 1.44861$ and afterwards it falls sharply at $n_2 = 1.44881$. It reveals that one should concentrate the design and fabrication of FRA maintaining the range of n_2 from 1.44801 to 1.44851 for the use of multiple pump and from 1.44861 to 1.44871 for the use of single pump. Fig. 11. gives the plot of phase matched wavelength vs. refractive index of second core. The curves depict the similar nature of trend as observed in the Fig. 9. But PMW's are closely lying within two super-modes. The achievement of high negative dispersion coefficient over C band in high values of refractive index will be able to compensate the accumulated dispersion in conventional single mode fiber [8].

4 Conclusion

We have presented an analysis of dual core single pump FRA in order to achieve its better performance with respect to the second core refractive index. This work highlights the gain characteristics as well as gives an advantage in dispersion compensation in the link by the choice of second core refractive index. We demarcate the two ranges of second core refractive index. The higher range of refractive index needs only single pump for gain flattening whereas the lower range requires multiple pumps for the same. We observe that when we increase the refractive index of second core in the higher side, we not only get gain flattening in the performance of FRA but also achieve more negative dispersion coefficient with the PMW varies slightly and closely lying within two super-modes. The achievement of high negative dispersion coefficient over C band in high values of refractive index of second core will be able to compensate the accumulated dispersion in conventional single mode fiber. Hence the high negative dispersion coefficient along with signal amplification makes FRA, a prospective candidate for Raman amplification and dispersion compensation. The results based on our investigation are in the lowest loss window of glass, and should invite attention of system designers to find wide uses to prescribe and design suitable FRA structure in amplifier optics and dispersion management.

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