Design of Nonzero Dispersion Flattened Fiber Amplifier Optimized for S-Band Optical Communication

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ABSTRACT: **We present a new design of dispersion flattened optical fiber for flat nonzero dispersion in the S-band region. The optimized parameters of optical fiber are used to find the optimum concentration of Tm-ions in Tm-doped optical fiber, which is further analyzed for the gain and noise performance. It is found that about 5000 mW of pumping power at 1.064 *m* is required to obtain 15 dB gain at 1.47 *m* in the silica glass Tm-doped (dispersion flattened) optical fiber.**

***Index Terms*—Excited-state absorption, optical fiber amplifier, Tm-doped amplifier (TDFA).**

I. INTRODUCTION

TO DATE, the C- and L-bands of optical communication (1.53–1.65 μm) are used for the data transfer over optical fiber link. Apart from the low loss, a reason for the popularity of these bands is the availability of erbium-doped optical fiber amplifiers operating in the C- and L-bands [1], [2]. However, an increase in the number of high-speed Internet users has made the C- and L-bands of optical communication almost fully utilized. Engineers are trying to use other bands of optical communication, such as 1.47 μm centered band (S-band) and 800-nm centered band [3]–[10]. For the S-band operation, the Tm-doped optical fiber amplifiers are the promising candidates because they operate around 1.47 μm. Recently, successful realization of a thulium-doped amplifier (TDFA) operating at 1.47 μm has been reported by our group [5], [11] for silica glass fiber and by others for silica glass fiber [6]–[8] and telluride/fluoride fiber [9]–[12]. To mention a specific case, a gain of about 20 dB with 1 W pumping power at 1065 nm has been predicted in the Tm/Al-doped silica glass fiber amplifier [6]. With regards to high-speed optical fiber communication that utilizes wavelength-division multiplexing (WDM), it is necessary to: i) manage dispersion by having flat dispersion over the entire band; ii) allow a small value of dispersion to avoid the Manuscript

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nonlinear issues like self-phase modulation, etc.; and iii) have an amplification in the band of optical communication. Earlier there were successful efforts to address these issues for Cand L-bands [13], and impressive work was also done for dispersion management with or without combination of amplifiers [14]–[20]. Although there are no S-band specific fiber designs reported so far, broadband fiber designs have been already proposed [21], [22]. In a special kind of fiber, a negative dispersion-flattened fiber for metropolitan networks (operating from O-band to L-band), which has dispersion value varying from

-10 to -5 ps/nm-km, has been reported [21]. Such fiber has a finite negative dispersion that is large enough to be accumulated over a long distance, necessitating the dispersion management schemes to increase the cost of the optical fiber network. In another approach, a flat-field fiber with a small dispersion slope of 9 ps/km-nm^{2}and a dispersion-compensating fiber operating in the range of 1.48 to 1.61 μm with dispersion of 6 ps/km-nm have been proposed [22], which are also susceptible to the problems of accumulated dispersion if used in the long-haul optical fiber communication link.

In the current communication, we propose a new design of optical fiber, which is optimized for near zero dispersion in the entire S/S+ band. Dispersion slope is far less (about –0.001 at 1.47 μm), giving a flat dispersion operation. The nonlinearity is nearly same as that of single mode fiber (SMF) and a low bending loss. Using the designed values of nonzero dispersion flattened fiber (NZDFF); we theoretically optimize and analyze the performance of Tm-doped amplifier under dispersion managed profile.

II. THEORY

A. Optical Fiber

The scalar wave equation for evolution of electrical field in the optical fiber is given as [23]

$$\frac{d^2E}{dr^2} = \frac{1}{r}\frac{dE}{dr} + \left(k_0^2 n^2(r) - \beta^2\right)E + \frac{L}{r^2}E \qquad (1)$$

E r k_0 $n(r)$ β

where is the electric field along fiber radius , is the propagation constant in the free space, is the efractive index profile of fiber, L is the azimuthal mode number, and is the propagation constant. The resolution of mode present in the optical fiber and the effective index calculations are done using the direct integration of scalar wave equation with appropriate boundary conditions. The induced chromatic dispersion (D) is computed from

(2)

$$D = \frac{-\lambda}{c}\frac{d^2 n_{\text{eff}}}{d\lambda^2}$$

n_{eff}

whereλ is the wavelength, is an effective index, and$c$is the speed of light in the vacuum.

The mode field diameter (MFD) of optical fiber is related to the field distribution in optical fiber, provides useful information about the microbending and the macrobending losses, and is directly related to the nonlinear distortions in the long-haul fiber link. The MFD can be calculated using the definition of effective

area(A_{eff}) of fiber as given

$$\text{MFD} = 2\sqrt{\frac{A_{\text{eff}}}{\pi}}$$

where can be evaluated using (3)

$$A_{\text{eff}} = \frac{2\pi\left(\int_r E^2 r dr\right)^2}{\int_r E^4 r dr}. \quad A_{\text{eff}}$$

(4) The macrobending loss is a radiative loss when the fiber bend radius is larger than the fiber diameter. In units of decibels/kilo-
meter, it is given as [23]

$$\alpha_{\text{macro}} = \frac{10}{\text{Log}_e 10}\left(\frac{\pi V^8}{16 R_c R_b W^3}\right)^{1/2} \times \exp\left(\frac{-4R_b \Delta W^3}{3R_c V^2}\right)\frac{\left[\int_0^\infty (1-g)E_0 r dr\right]^2}{\int_0^\infty E_0^2 r dr} \qquad (5)$$

where E_0 is the radial field of fundamental mode, r_c denotes the fiber core radius, n_{max} and n_{min} are the maximum and minimum values of refractive index, respectively, β is the propagation constant of mode, k_0 is the propagation constant in the vacuum, and other parameters appearing in the above equation are given by

(6)

$$g = \frac{n(r)^2 - n_{\text{min}}^2}{n_{\text{max}}^2 - n_{\text{min}}^2}$$

(7)

$$V = k_0 r_c \sqrt{n_{\text{max}}^2 - n_{\text{min}}^2}$$

(8)

$$W = r_c\sqrt{\beta^2 - (k_0 n_{\text{min}})^2}$$

(9)

$$\Delta = \frac{n_{\text{max}}^2 - n_{\text{min}}^2}{2n_{\text{max}}^2}.$$

The microbending loss is a radiative loss in fiber resulting from the mode coupling caused by random microbends, which are repetitive small-scale fluctuations in the radius of curvature of fiber axis. An approximate expression for microbending

$$\alpha_{\text{micro}} = A(k_0 n_{\max} \text{MFD})^2 (k_0 n_{\max} \text{MFD})^{2p}$$

A is a constant and p is the exponent in the power law.
attenuation coefficient is given by [24] (10)

where

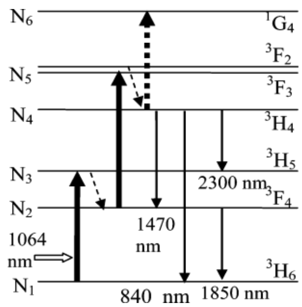


Fig.1. Energy level diagram for Tm^{3+} ions in the silica glass optical fiber

B. Tm-Doped Amplifier

The energy levels of Tm ions doped in the silica glass fiber are shown in Fig. 1. When the Tm-doped optical fiber is pumped with a 1064 nm laser, six energy levels are involved. The pump absorptions are at the energy level $^3H_6$ [by the ground state absorption (GSA)] and at the energy level $^3F_4$ [by the excited state absorption (ESA)]. In the silica glass TDFA, the ESA $^3F_4 \rightarrow$ $^3F_{2,3}$ is very strong as compared to the GSA. Another ESA $^3H_4 \rightarrow {}^1G_4$ is very weak in the TDFA with Tm-ion concentration below a few 10^{26} ions/m^3 and, hence, can be neglected. The 1064 nm pumped TDFA has $^3H_4$ level-initiated emissions at 2100, 1470, and 840 nm with typical branching ratios of about 2%, 10%, and 88%, respectively.

In the case of silica glass fiber TDFA, the simplified rate
equations can be derived using certain approximations as follows. The nonradiative decay rates of Tm-ions from $^3F_3$ and $^3H_5$ levels to respective underlying levels are high ($> 10^5$ s^{-1}). Therefore, the atomic population densities at levels N_5 and N_3 are very small and can be neglected, i.e., $N_3 = N_5 = 0$. The emission cross-sections $\sigma_{31p} = \sigma_{52p} = 0$ because there is no emission at 1064 nm in the Tm-doped silica glass fiber. The nonradiative transition rate A_{nr4} is also very high as compared to the radiative transition rate $A_{r4j(j=1,2,3)}$, and, hence, we can write

$$(A_{r42} + A_{r43} + A_{nr4}) \approx (A_{r41} + A_{r42} + A_{r43} + A_{nr4}) \equiv 1/\tau_4 \tag{11}$$

where τ_N is the fluorescence lifetime of layer N and is defined as $A_{rN} + A_{nrN} = 1/\tau_N$. The rate equations considering the significant levels N_1, N_2, and N_4 are then written as [5]

$$\frac{dN_2}{dt} = N_1 W_{13p} + N_4 \left(W_{42s} + \frac{1}{\tau_4}\right) - N_2 \left(W_{25p} + W_{24s} + \frac{1}{\tau_2}\right) \tag{12}$$

$$\frac{dN_4}{dt} = N_2(W_{24s} + W_{25p}) - N_4 \left(W_{42s} + \frac{1}{\tau_4}\right) \tag{13}$$

with

$$N_0 = N_1 + N_2 + N_4 \tag{14}$$

$$N_0 = N_1 + N_2 + N_4 \tag{14}$$

TM-DOPED OPTICAL AMPLIFIER PARAMETERS USED IN THE CALCULATIONS

$\tau_2 \approx 454 - 12\times C$ μs ($^3F_4$),
$\tau_4 \approx 41.5 - 1.2\times C$ μs ($^3H_4$)
$P_s(0) = 5$ μW
Signal wavelength (λ_s) = 1470 nm
Pump wavelength (λ_p) = 1064 nm
$\sigma_{13p} = 0.05\times 10^{-25}$ m^2 at λ_p
$\sigma_{24p} = 4\times 10^{-25}$ m^2 at λ_p
$\sigma_{24s} = 1.2\times 10^{-25}$ m^2 at λ_s
$\sigma_{42s} = 2.1\times 10^{-25}$ m^2 at λ_s
$\alpha_p \approx 0.05 + 0.25\times C$, $\alpha_s \approx \alpha_p/5$
where C is the Tm-ion concentration in 10^{25} ions/m^3

where $W_{ij(s,p)} = \sigma_{ij(s,p)}(I_{s,p}/h\upsilon_{ij})$, I is the intensity in W/m^2, σ is the cross-section in m^2, υ is the frequency in hertz, subscripts s and p stand for signal and pump, respectively, h is Planck's constant, A_r is the radiative transition rate in s^{-1}, A_{nr} is the nonradiative transition rate in s^{-1}, N_k is the Tm-ion population density at kth level, t is the time, and N_0 is the total Tm-ion concentration in ions/m^3. In the above model, the ESA from $^3H_4$ to $^1G_4$ level is neglected, as it is insignificant in the silica glass fiber TDFA with low concentration of Tm-ions.

The steady-state solution of (12)–(14) can be used to find the population densities of energy levels. Considering the amplification of spontaneous emission (ASE) is propagating independent of signal, the evolutions of signal and pump intensities with the fiber length parameter z are given as [5]

$$\frac{dI_p}{dz} = -(\sigma_{13p}N_1 + \sigma_{25p}N_2)I_p \quad (15)$$

$$\frac{dI_s}{dz} = (\sigma_{42s}N_4 - \sigma_{24s}N_2)I_s \quad (16)$$

with

$$N_1 = N_0\frac{(1+\tau_4W_{42s})}{1+\tau_4W_{42s}+\tau_2W_{13p}\,(1+\tau_4(W_{25p}+W_{24s}+W_{42s}))} \quad (17)$$

$$N_2 = N_0\frac{\tau_2W_{13p}(1+\tau_4W_{42s})}{1+\tau_4W_{42s}+\tau_2W_{13p}\,(1+\tau_4(W_{25p}+W_{24s}+W_{42s}))} \quad (18)$$

$$N_4 = N_0\frac{\tau_2\tau_4W_{13p}(W_{24s}+W_{25p})}{1+\tau_4W_{42s}+\tau_2W_{13p}\,(1+\tau_4(W_{25p}+W_{24s}+W_{42s}))}. \quad (19)$$

TABLE I

radius and are the optical fiber parameters that are defined as , , and , in which , is the propagation constant and is the core refractive index. For the step index single-mode fiber, an empirical relationship can be used for the known number [25]. It is noted that as the ASE has not been accounted for in (14) and (15), the model is valid only for gain less than about 20 dB.

The evolution of pump and signal powers along the length of optical fiber can be stated as

$$\frac{dP_p}{dz} = -\left(2\pi\int_0^a(\sigma_{12p}N_1+\sigma_{24p}N_2)f_prdr+\alpha_p\right)P_p \quad (20)$$

$$\frac{dP_s}{dz} = \left(2\pi\int_0^a(\sigma_{42s}N_4-\sigma_{24s}N_2)f_srdr-\alpha_s\right)P_s \quad (21)$$

where α is the attenuation at pump (p) or signal (s) wavelength. The Tm-doped amplifier can be easily analyzed using (15)–(21). Considering an independent evolution of noise power in the optical fiber, the variation of noise power with respect to the fiber length can be shown to be [26]

$$\frac{dP_n}{dz} = (2h\upsilon_{24}\Delta\upsilon)\left(2\pi\int_0^a(\sigma_{42s}N_4)f_srdr\right) + \left(2\pi\int_0^a(\sigma_{42s}N_4 - \sigma_{24s}N_2)f_srdr - \alpha_s\right)P_n \quad (22)$$

where P_n is the noise power and $\Delta\nu$ is the optical bandwidth (in meters) of filter used to measure the noise power. The noise figure (NF) is then calculated using

NF(dB) (23)

III. DESIGN OF NZDFF FIBER

There are total six parameters to be optimized for the near zero-dispersion value and they are: . To simplify the task, we first fixed the refractive index (RI) values (n_1, n_2, and n_3). The values were chosen that are typical for the optical fiber fabricated using the modified chemical vapor

$(dN_i/dt = 0)$

The relationship between fundamental mode intensity and

power is given as , where is the power and $I_p = f P_p$ P f

is the transverse dependency of mode intensity pattern, which is normalized so that , where is the radial parameter of optical fiber. When both the signal and pump powers are at fundamental mode, the value of is given by the Gaussian envelope approximation that provides a better match with the radial intensity distributions of pump and signal [1], [25] and is expressed as ; $2\pi \int_0^\infty f r dr = 1$

, in which is the mode field

radius at signal wavelength, is the mode field radius at pump wavelength, and is the mode field area at pump wavelength. The mode field radius is given as , where is the core

r

f

$f_p = Exp(-r^2/w_p^2)/\pi w_p^2$ $\quad f_s = Exp(-r^2/w_s^2)/\pi w_s^2$ $\quad w_s$ $\quad w_p$ $\quad A$ $\quad (= \pi w_p^2)$

$w = aJ_0(U)VK_1(W)/(UK_0(W))$ $\quad a$ $\quad U, W, V$

$U = a(k_0^2 n^2 - \beta^2)^{1/2}$ $\quad W = a(-k_0^2 n^2 + \beta^2)^{1/2}$

$U^2 + W^2 = V^2$ $\quad k_0 = 2\pi/\lambda$ $\quad \beta$ $\quad n$

$W = 1.1428V - 0.996$ $\quad V$

$$= 10\text{Log}_{10}\left(\frac{\frac{P_n(z)}{hv_{24}\Delta v} + 1}{P_s(z)/P_s(z=0)}\right).$$

a, b, c, n_1, n_2, and n_3

deposition (MCVD) process and that are known due to the experience of authors in the fabrication of optical fibers. This way of fixing RI values can be justified by two ways: first, it reduces the task of optimization (because then the parameters to be optimized are reduced to three), and second, and most important, it avoids impractical values of RI. Theoretically obtained values can be excellent on paper but difficult to achieve practically in the MCVD system. During the practical realization of fiber, the width parameters can be controlled far more easily than the RI parameters. For example, if the radius of fabricated preform is above the design value, the preform can be jacked or elongated to obtain desired value of radius; this freedom is not available for RI values. Therefore, we chose the RI values achievable with

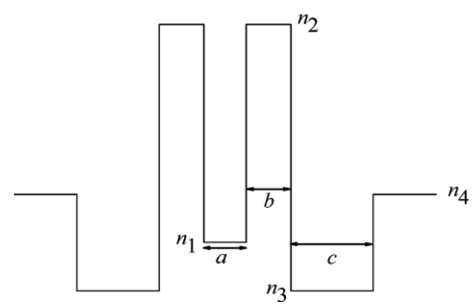


Fig. 2. Proposed profile structure for dispersion flattened nonzero dispersion flattened fiber.

TABLE II DESIGN PARAMETERS OF NZDFF FIBER AT 1.47 m

a (μm)	b (μm)	c (μm)	n_1	n_2	n_3	n_4
1.0	2.12	3.9	1.443	1.452	1.441	1.445

LP_{11} cutoff = 947 nm

A_{eff} at 1.47 μm = 49 μm^2

Dispersion = 0.013 ps/(km.nm)

MFD = 6.68 μm @ λ = 1064 nm

= 7.9 μm @ λ = 1470 nm

a typical MCVD system. Once the RI values are fixed, the (a, b, c) width parameters can be varied theoretically to obtain the near zero dispersion value. We used commercial FiberCAD software to solve the scalar wave a, b, c equation (1) for the profile of Fig. 2. The values of parameters were varied repetitively to achieve the near zero dispersion value (<0.05 ps/(km-nm) at 1.47 μm and care was taken to disallow the variation of dispersion that was more than 0.5 ps/(km-nm) for the spectral range of 1.45 to 1.5 μm. To calculate the bending losses, we used a bending radius of 38 mm in (5) and $A = 5 \times 10^{-14}$ and $p = 2$ in (10).

To calculate the amplification of TDFA, (20) and (21) were solved for the evolution of signal and pump powers with distance. The parameters used in the calculation are listed in Table I. Radial rare earth ion concentration profile was considered to be stepwise, i.e.,

Tm-ion concentration
$= N_0$ for $r <= (a + b)$
$= 0$ for $r > (a + b)$.

IV. RESULTS AND DISCUSSION

The proposed refractive index profile of the nonzero dispersion flattened fiber is shown in Fig. 2. The optimized design parameters are listed in Table II, where all μ values are with reference to 1.47 m wavelength. μ The solution of scalar mode equation at 1.47 m givesthe modefield pattern as shown in Fig.3(a) for the three-dimensional view and in Fig. 3(b) for the radial two-dimensional view.

The spectral variations of effective RI and group delay can give rise to the dispersion flattened effect. Such variation calculated using (1) is shown in Fig. 4 for the fiber design parameters

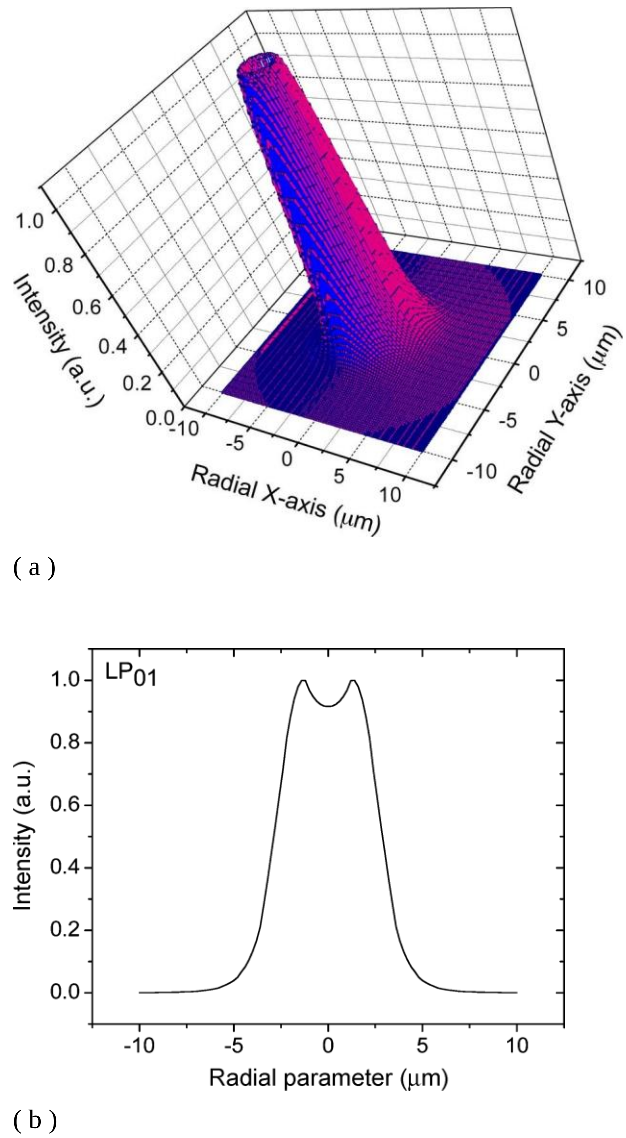


Fig. 3. (a) Mode-field topological pattern at 1.47 m. The view is tilted so that mode-field dip at the center is clearly visible. (b) Radial variation of LP $_{01}$mode-field pattern at 1.47 m.

of Table II. The variation of dispersion of proposed fiber calculated using (1) and (2) is shown in Fig. 5(a). It can be observed that the dispersion is nearly flat in the band around 1.47 m. μ

The dispersion slope along with the dispersion has been plotted in Fig. 5(b), where a very small dispersion slope of 0.001 at 1.47 μm can be observed, proving the flatness of dispersion in the amplification band of Tm-doped amplifier. The dispersion slope is far better than the earlier reported results [21], [22].

The long-haul optical fiber communication link contains the conventional SMF and therefore the dispersion managed fibers are needed to be spliced to the SMF. To minimize the splice loss, the mode field diameter of NZDFF should be nearly equal to that of SMF because in the optical fiber link, it is the SMF that is going to be connected with the NZDFF fiber. The SMF has an MFD of about 7 to 9μm at 1.47 m. The spectral variation of MFD of NZDFF fiber is shown in Fig. 6. It can be observed that the MFD of NZDFF fiber is 7.9 m at 1470 nm, which

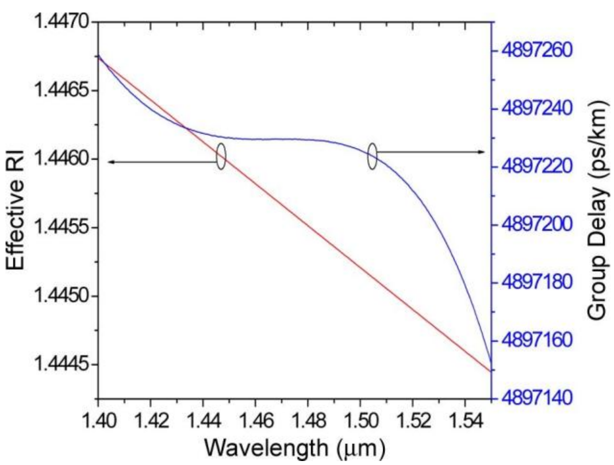
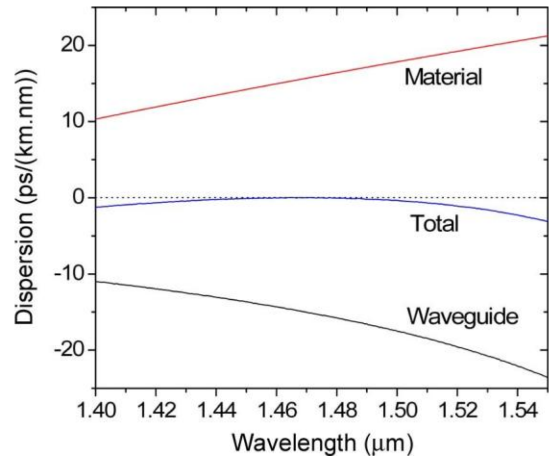
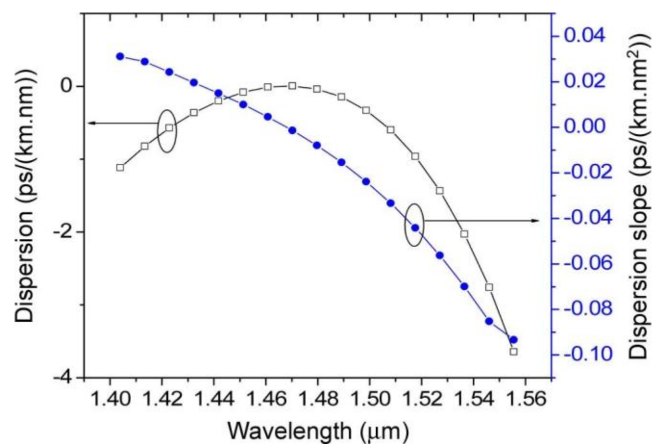


Fig. 4. Spectral variations of effective refractive index and group delay.



(a)



(b)

Fig. 5. (a) Spectral variation of material, waveguide, and total dispersion. Total dispersion is very flat and nearly zero at 1.47 m window (dispersion ps/(km-nm) at 1.47 m). (b) Spectral variation of dispersion and dispersion-slope.

matches fairly well with the MFD of SMF. With regard to the bending loss, as most of the double or triple core optical fibers havelargebendingloss,wechoseawidewidthofnegativeindex

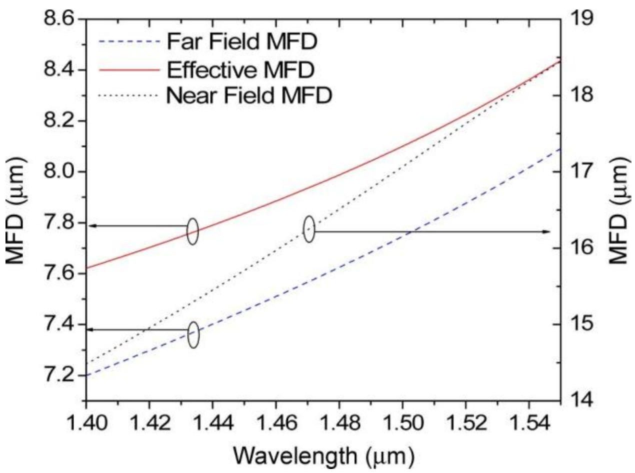


Fig. 6. Spectral variations of mode field diameter. The effective MFD at 1.47 m is 7.9 m.

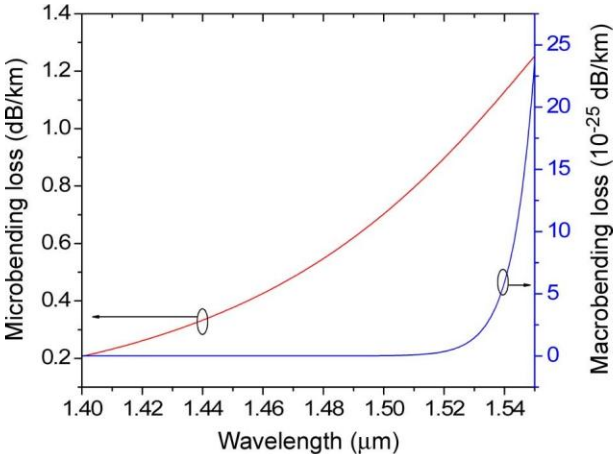


Fig. 7. Spectral variations of bending loss. For practical amplifier, the bending loss is very low as length is limited to a few tens of meters.

region (c), which resulted into the negligible bending loss as shown in Fig. 7. The bending loss was calculated using (5) for a bending radius of 38 mm. Fig. 7 also shows the estimation of microbending loss calculated from (10). It is noted that the microbending loss is just an estimation and can be brought down to a negligible value by carefully controlling the diameter of optical fiber.

To understand the sensitivity of design parameters, we changed one of the design parameters while keeping all other parameters constant and calculated the dispersion. Resulting graphs are shown in Fig. 8(a) for the variation in radial parameter (, , or) and in Fig. 8(b) for the variation in RI parameter (, , or). It can be observed that among all radial parameters, parameter is more sensitive to change in its magnitude; a slight change in its value can cause a wide dispersion shift. The reason behind this can be explained as follows. Parameter b is a part of the core where most of the electric field is distributed and is also a separation between inner cladding and outer cladding. Any increase in the value of will cause the mode field to be tightly confined in the core, thereby increasing the dispersion. However, the decrease in will cause a change in electrical field distribution, where it leaks to the outer clad,

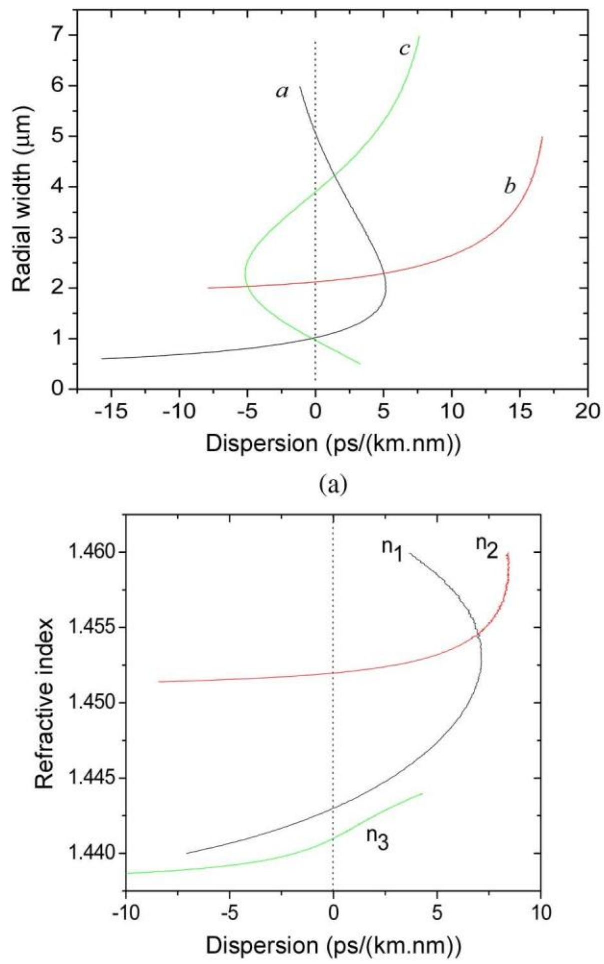


Fig. 8. Effect on spectral variation of dispersion if one of the design parameters (a) radial width and (b) refractive index is changed and other parameters are unchanged.

a b c n_1 n_2 n_3 b

b

which eventually changes the second-order variation of n_{eff}. That is why a small change in b can bring a large change in the dispersion value. In the case of RI parameters, all of them cause significant shift in the dispersion with change in their values, which indicates the electric field distribution dependency on RI.

To estimate the effect of our design parameters over the nonresonant third-order nonlinearity, we calculated the spectral variation of effective nonlinear (n_2) index as shown in Fig. 9. It can be observed that the n_2 at 1.47 μm is

$= 2.88 \times 10^{-16}$ cm^2/W, which is quite similar to the SMF

fiber.

With regard to the Tm-amplifier, we used the optimized parameters of NZDFF and its electric field distribution and solved (20)–(22). Fig. 10 shows the variation of Tm-ion concentration needed to get the constant gain at various pump powers. This curve is useful to estimate the optimum concentration of Tm ions that will require the lowest pump power (at 1.064 μm) to achieve predetermined gain at 1.47 μm. A U-type curve can be observed in the concentration-power variation curve of TDFA to get the predetermined gain (as shown in Fig. 10). When the rare-earth ions' concentration is low in the core of optical fiber

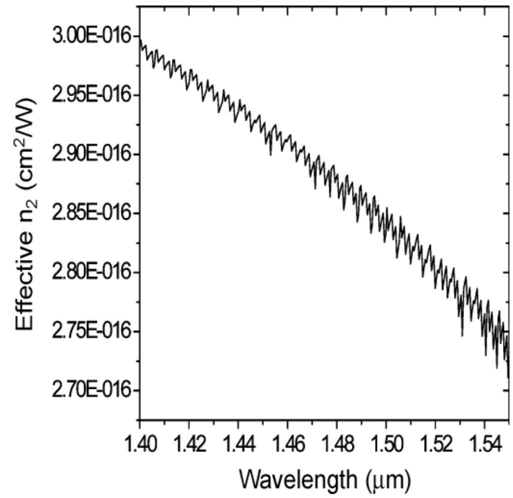


Fig. 9. Variation of nonlinear RI with respect to wavelength. Nonlinear RI 2 at 1.47 m is 2.9 10^{-16}, which is similar to the single mode fiber.

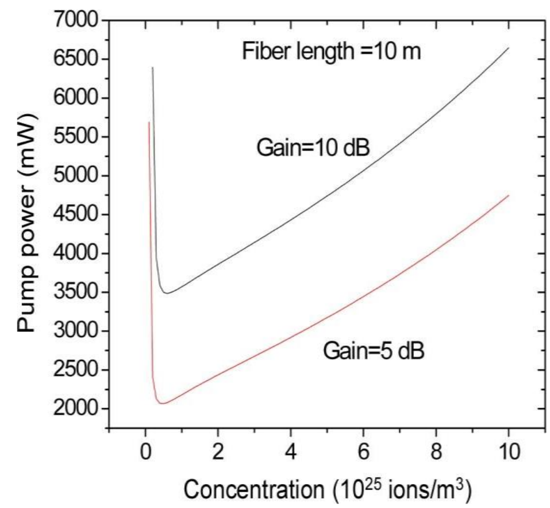


Fig. 10. Optimum concentration for minimum pump power requirement at different gains. (Fiber length m.)

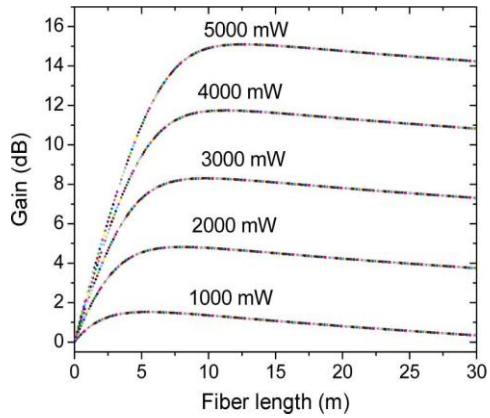


Fig. 11. Variation of gain with the fiber length. (Concentration 10^{25} ions/m^3.)

(length = 10 m), a very large pumping power is needed to excite a sufficient number of rare-earth ions from the ground state to the higher energy state so that a predetermined gain can be achieved. However, the absorption of fibers with the same fiber length of 10 m increases in proportion to the rare-earth

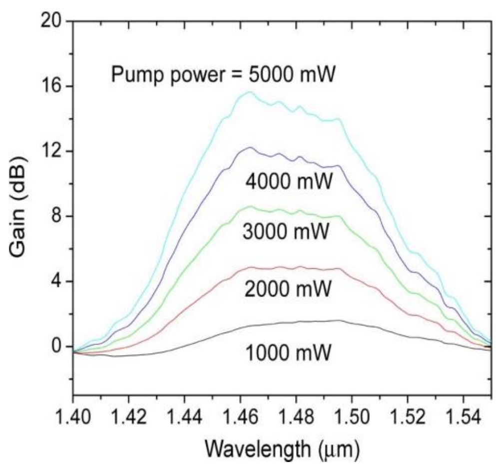


Fig.12. Spectral variation of gain at different pump powers (Fiber length m, Concentration ^{25} ions/m^3.)

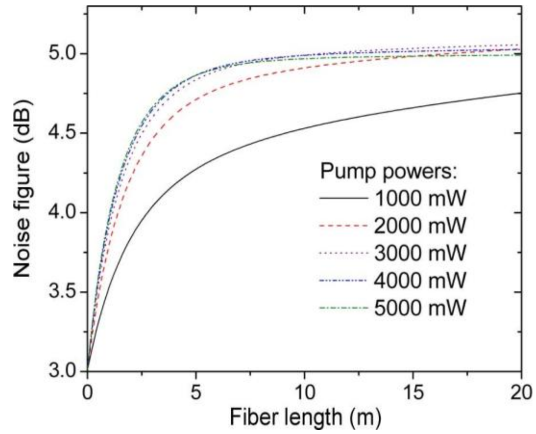


Fig. 13. Variation of noise figure along fiber length at different pump powers.

concentration. As shown in Fig. 10, the signal gain decreases owingtothehighconcentrationdopingat thesamepumppower. This is due to increased spontaneous absorption in the signal band of the highly doped fiber because the average pump power in the whole fiber is low owing to the high concentration at pump wavelength, which forms the low population inversion state. Optimum concentration of Tm-ions can be seen to be 0.5 10 ions/m . It can be noted that a very high pumping power at 1.064 m (3500 mW) is needed to achieve 10 dB gain at 1.47 m for 10 m of fiber. When the optimum concentration of Tm-ions is used, calculated gain variation with respect to the fiber length at various pump powers is shown in Fig. 11. It is observed that 5000 mW of power at 1.064 μm is needed to achieve 15 dB gain at 1.47 m. This indicates the fact that silica glass fiber Tm-amplifier is an inefficient system of amplification. The spectral variation of gain of NZDFF-TDFA for different pump powers at 1.064 m (length = 10 m) is shown in Fig. 12. A wide band of gain can be observed, and this indicates that the NZDFF-TDFA is useful for optical wavelength-division multiplexed systems. Incidentally, for the 200 km of NZDFF, the maximum bit rate possible at 1.47 μm will be above 96 Gb/s for laser source spectral width of 1 nm. Another factor for the amplifiers, i.e., the noise figure, is an important factor as a high noise figure deteriorates the performance of amplifier. The evolution of noise power was calculated from (22), and NF was determined using (23) for a fiber length of 10 m. As shown in Fig. 13, the NF is 5 dB for 5000 mW of pump power at 1064 nm, which is quite higher than the lower limit of 3 dB.

V. CONCLUSION

A new design of nonzero dispersion flattened optical fiber has been proposed, which has given a flat dispersion in the band of 1.4 to 1.55 μm with the dispersion slope of –0.001 at 1.47 μm. The Tm-doped amplifier optimized for simultaneous amplification and dispersion management showed that about 5000 mW of pump power at 1064 nm will be needed to achieve