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# Transmission Techniques for Ultra Dense Wavelength Division Multiplexing By Using Two Optical Amplifiers in Nonlinear Optical Networks

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-------------------------------------------------------------------**ABSTRACT**--------------------------------------------------------------
In the present paper, the problem amplification techniques of ultra dense wavelength division multiplexing (UDWDM) in nonlinear optical networks are investigated through five transmission techniques. The impact of tailoring of chirped pulses of different temporal waveforms is investigated in a normal dispersion fiber. The set of multiplexed signals are tailored in a different a subset to assure approximately the same output level of power to hold the signal-to-noise ratio at the same level. Moreover, three different transmission techniques, namely, soliton propagation, maximum time division multiplexing (MTDM) and "Shannon" capacity, are employed where successive section of alternating dispersion are used as a technique to manage the dispersion. Distributed "Raman" amplifiers as well as Erbium doped fiber amplifier are engaged to maximize the repeater spacing. We have succeeded to multiplex 2400 (UDWDM) channels in the optical range 1.45 — 1.65 μm with channel spacing ranging from 0.3 up to 0.6 nm where each channel has its own characteristic parameters of loss, dispersion, and amplification. The channels are divided into sub-groups ( each of 4, 5, 6, 7,….,24 ) where the technique of space division multiplexing (SDM) is applied. The multispan effects of "Kerr" nonlinearity and amplifier noise on "Shannon" channel capacity of dispersion-free nonlinear fiber is considered as a ceiling value for the sake of comparison. The case of soliton with modified Raman amplification via parametric gain also is investigated. Each link has special chemical structure, optical signals power, and optical Raman pumping. The cable contains {4, 5, 6, 7,…. , 24} links in SDM. It has been shown that the modified Raman gain yields higher effects on the variable under consideration if compared with the conventional Raman gain. The number of links is in positive correlations with the set of effects {Repeater spacing, Soliton product, MTDM product}. In general Shannon product is the ceiling but it undergoes a maximum value at twelve links. The Chirping product also possesses a maximum at 8 links.

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## 1. Introduction

The propose of a WDM passive optical network (PON) to provide conventional unicast data and downstream multicast function. The proposed scheme is experimentally demonstrated with 1.25 Gb/s downstream unicast, multicast and upstream data [1]

Optical transmission using dispersion managed (DM) transmission line composed of standard (non dispersion shifted) single mode fiber (SMF) and dispersion compensation fiber (DCF) is very important in terms of developing high-speed time division multiplexed (TDM) and WDM systems. Sahara et al. [2] analyzed numerically and in detail a 40 Gbit/s return-to-zero (RZ) transmission system over a transoceanic distance in strongly dispersion managed line composed of standard single-mode fiber (SMF) and DCF [3,4].

WDM which is simply the technique of communicating multiple data streams on separate wavelengths, has emerged as a powerful communications technology. Architectural considerations for deployment of ultra-wideband (1450-1650 nm) WDM networks having a massive number of WDM channels (400-1000) are investigated [5,6,7,8] for MAN /WAN networks.

Distributed Raman Amplification (DRA) is attracting an increasing allention as a key technology to increase the capacity and / or reach of WDM transmissions systems since this can improve the optical signal – to– noise ratio with minimum additional waveform distortion due to nonlinear effects [9,10].

Ho et.al [11] had studied theoretically and experimentally fiber OPAs with a bandwidth on the order of 200 nm. Under these circumstances, the OPA gain significantly overlaps the pump-induced Raman gain, which peaks at about 110 nm from the pump, on the long wavelength side. It then becomes necessary to study the combined effect of the two separate gain mechanisms.

Ho et.al theoretically investigated the influence of the Raman gain on a broadband fiber OPA. It was found that for a high-gain amplifier, the Raman effect should introduce only a relatively small distortion of the pure OPA gain spectrum in the form of an increase (decreases) on the long (short) wavelength side.

In the present paper, through deep parametrical study, we investigate through two multiplexing techniques (UDWDM and SDM) the transmission of 2400 channels employing five different propagation techniques, namely classical Raman, modified Raman, maximum time division multiplexing, chirped pulses and "Shannon" capacity where the amplification is carried out via the engagement of Raman amplification plus erbium-doped fiber amplifier (EDFA).

## 2. Basic Model and Analysis

Special type of fiber of low less over the range 1.2 μm up to 1.65 μm must be used. This fiber dubbed "AllWave" its losses which is depicted in [10] challenge us to think of new ways to fill its generous bandwidth employing the technique of UDWDM. The data of "AllWave" fiber is cast under the form in units of dB/km

$$\sigma(\lambda) = 0.19 + 7.04(\lambda - \lambda_m)^2 + 34.06(\lambda - \lambda_m)^3 + 72.11(\lambda - \lambda_m)^4 + 36.7(\lambda - \lambda_m)^5 \quad (1)$$

with $1.2 \le \lambda,\ \mu m \le 1.65$, where $\lambda_m$ is the minimum loss optical wavelength, $\lambda_m$=1.55μm

The distance between two successive repeaters is $Z_{iR}$ where it is calculated based on the model of [2,4,12,13], but, taking into account the interaction or cross-coupling effect. As the powers of signal $P_S$ and Raman pumping $P_R$ undergo variations according to:

$$\frac{dP_{si}}{dz} + \sigma_{si} P_{si} = [\alpha P_R + (\beta_1 - \beta_2) P_{si}] P_{si} \quad (2)$$

$$\frac{dP_R}{dz} + \sigma_R P_R = -\beta_3 P_{si} P_R \quad (3)$$

The solution of these two nonlinear coupled differential equation is given:

$$P_{si}(z) = \left[ \frac{P_{sio}(1+\beta_e)}{1+\beta_e e^{-K_i}} \right] e^{-\sigma_{si} z} \quad (4)$$

where $P_{sio}$, $\beta_e$, and $K_i$ respectively are:

$P_{sio}$ : is the tailored input power of i-th. Signal,

$$\beta_e = \sum_{i=1}^{N} (\beta_1 - \beta_2) / \text{No. of channels}$$

$$K_i = k_i (1 - e^{-\sigma_R z})$$

In this situation, $P_{si}(z)$ increases at first due to Raman amplification then, it begins to decrease till its value reaches to the amplified spontaneous emission ASP [2]. At this distance, the signal decreases due to the natural decay to $10^{-3}$ ASP then EDFA raise the level to ASP again as its gain is 30 dB. Thus $Z_{iR}$ is the distance at which:

$$P_{si}(z_R) = 10^{-3} \text{ASP} \quad (5)$$

This distance $Z_{iR}$ is employed in the differed processed techniques that compute the system soliton bit rate $B_{rsi}$ of the i-th. channel as follows:

### a) The soliton technique:

$Z_R$ has no effect, as we get $B_{rsi}$ a distance-free quantity [3,14] as:

$$\frac{P_{sio}}{B_{rsi}^2} = 59.7 \left( \frac{\lambda_{si}}{1.54} \right)^3 \left( \frac{A_e}{20} \right) \left( \frac{3.2x10^{-20}}{n_2} \right) . |D_t| x10^6 \quad (6)$$

$A_e$: is the effective cross section, $\mu m^2$

$n_2$: is the nonlinear refractive index coefficient, where $n_2$ (pure silica) is given by $n_2 = 3.2x10^{-19}$ $m^2$/Watt while for germania doped silica $n_2$ is given by:

$$n_2 = 3.2x10^{-19}(1.0 + 2.81294x - 16.6123x^2 + 45.9808x^3) \quad (7)$$

where x is the percentage of Germania in the Germania-doped silica fiber.

$|D_t|$ : is the total dispersion coefficient, psec/(km.nm)

### b) The maximum time division multiplexing technique (MTDM)

In this technique, the MTDM bit rate of the i-th. channel is $B_{rmi}$ where [14,15]:

$$B_{rmi} = \frac{1}{4\tau_{mi}(\lambda_{si}, z_{iR}, \tau_{io}, N_o)} \quad (8)$$

where:

$\tau_{mi}$ : is the pulse width at distance $z_{iR}/N_o$ of the i-th. channel

$N_o$ : is the number of successive sections of alternative dispersion

$\tau_{io}$ : is the initial pulse width

### c) Chirped pulses technique

The pulse width in this technique is reduced due to the initial chirp [13,14,16, 17] as given by:

$$\tau_{csi} / \tau_{cio} = \sqrt{1 + 0.543\mu((z_{iR} + z_o)/N_o)^2} \quad (9)$$

or exactly:

$$\tau_{csi} / \tau_{cio} = \sqrt{1 + 0.543\mu((z_{iR} + z_o)/N_o)^2} - a_o \quad (10)$$

where $\tau_{csi}$ and $\tau_{cio}$ are respectively the chirped pulse width and the initial pulse width of the i-th. channel. In this technique the initial chirp reduce the total dispersion coefficient and consequently reduces $\sigma_{si}$ and gives the chirped bit rate of the i-th. channel $B_{rci}$ as: $B_{rci} = \frac{1}{4\tau_{csi}}$ (11)

### d) Shannon Product

Tang [18-22] presented a ceiling value of "Shannon" capacity of multichannels, and multispans dispersion-free nonlinear optical fiber taking into account the effects of multispan, "Kerr" nonlinearily and amplifier noises where "Shannon" capacity is cast as shc, where:

Volume:02, Issue:02, Pages: 562-569 (2010)

$$shc = BW\ Log_2\left[1+\left(\frac{C}{N_s^2 N_c k_{ci}(P_W BW_i)}\right)^{2/3}\right] \quad (12)$$

and consequently the "Shannon" product in Tbit.km/sec is:

$$shp = \sum_{i=1}^{N_c} BW_i.L_s\ Log_2\left[1+\left(\frac{C}{N_s^2 N_c k_{ci}(P_W BW_i)}\right)^{2/3}\right] \quad (13)$$

where:

$BW_i$ : is the channel bandwidth, THz

i: is indicates that the computation is at $\lambda_{si}$

$L_s$: is the span length, km

$N_c$: is the number of channel, = 2400

$N_{cL}$: is the number of channels / link = $N_c/N_L$

$N_L$: is the number of links(4,5,6,7,…..,24)

$N_s$ : is the number of sections

C: is a constant (dimensionless), = 1.9746

$k_{ci}$:is a constant related to the "Kerr" nonlinear coefficient, $W^{-1}$

$P_W$: is the noise power density, W/THz

where:

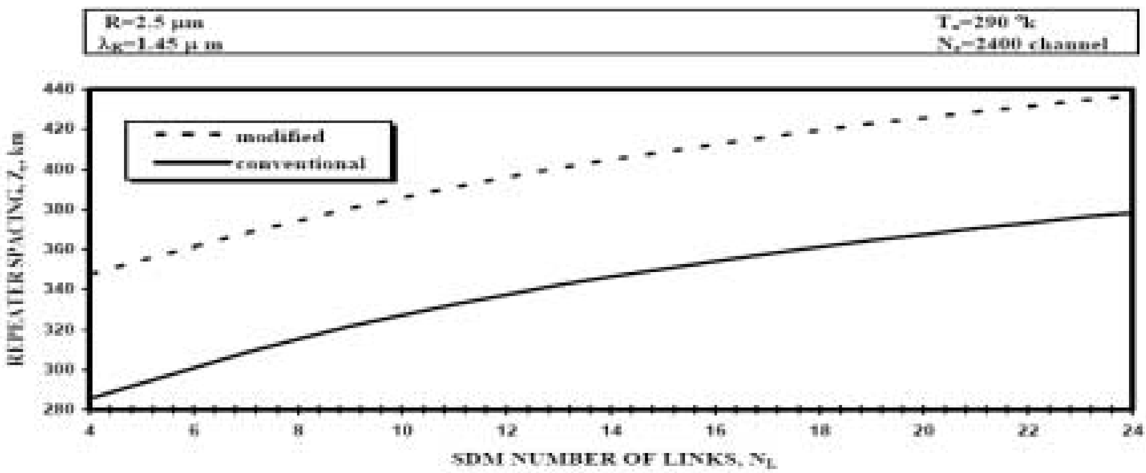


**Fig. 2. Variations of repeater spacing against variations of SDM number of links at the assumed set of parameters.**

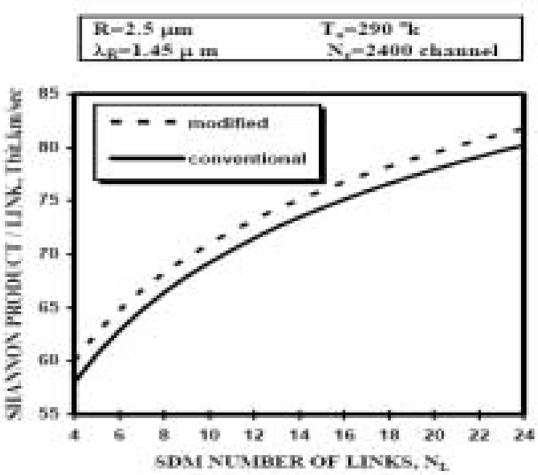


**Fig.3 Variations of Shannon product/link, Tbit.km/sec against variations of SDM number of links at the assumed set of parameters.**

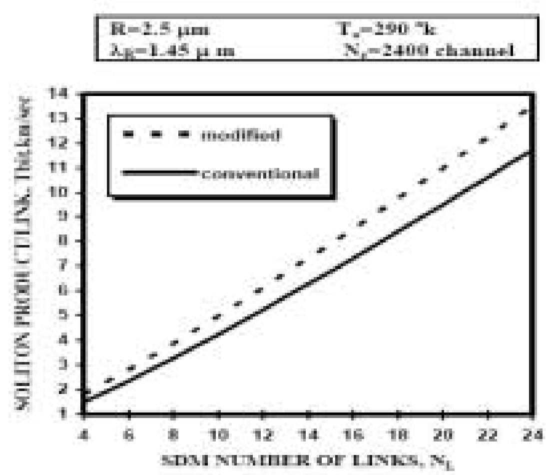


**Fig.4. Variations of soliton product/link, Tbit.km/sec against variations of SDM number of links at the assumed set of parameters**

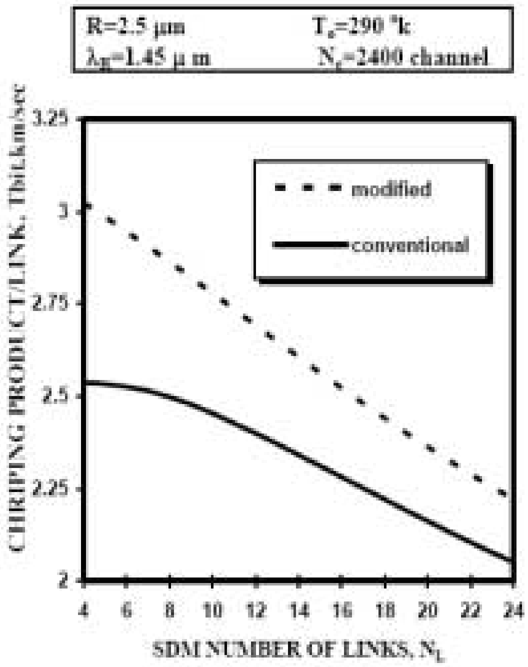


**Fig.5. Variations of chirping product/link, Tbit.km/sec against variations of SDM number of links at the assumed set of parameters.**

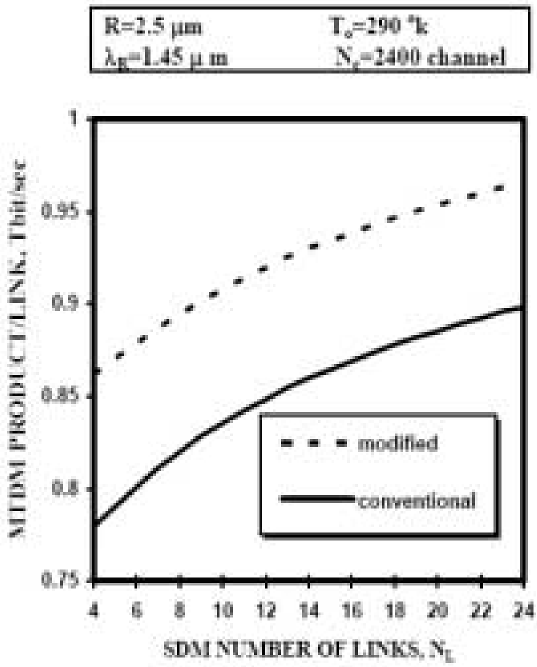


**Fig.6. Variations of MTDM product/link, Tbit.km/sec against variations of SDM number of links $_L$ at the assumed set of parameters**

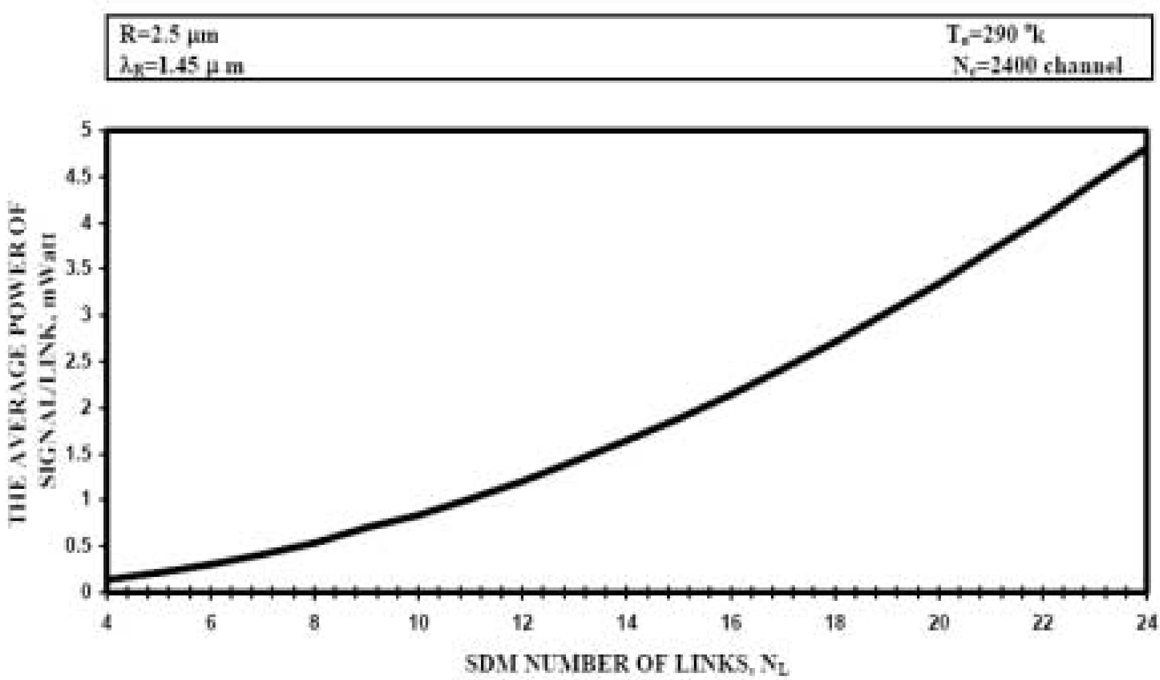


**Fig. 7. Variations of $P_{S,ave}$ against variations of SDM number of links at the assumed set of parameters.**

| | |
|---|---|
| R=2.5 μm | $T_o$=290 °k |
| $\lambda_R$=1.45 μ m | $N_c$=2400 channel |

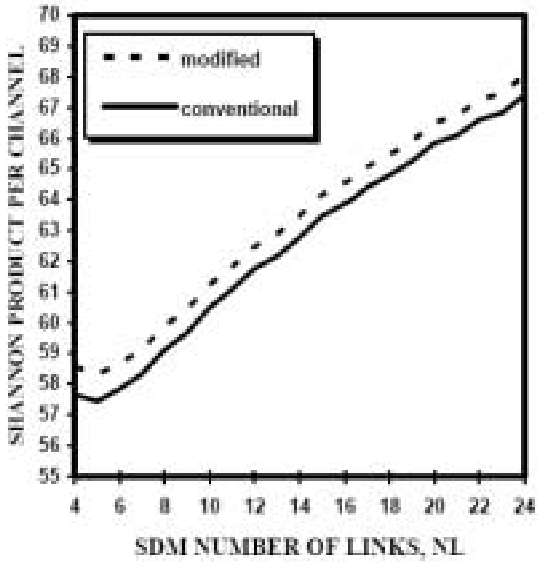


**Fig.8.** Variations of Shannon product/channel, Tbit.km/sec against variations of SDM number of links, $N_L$ at the assumed set of parameters

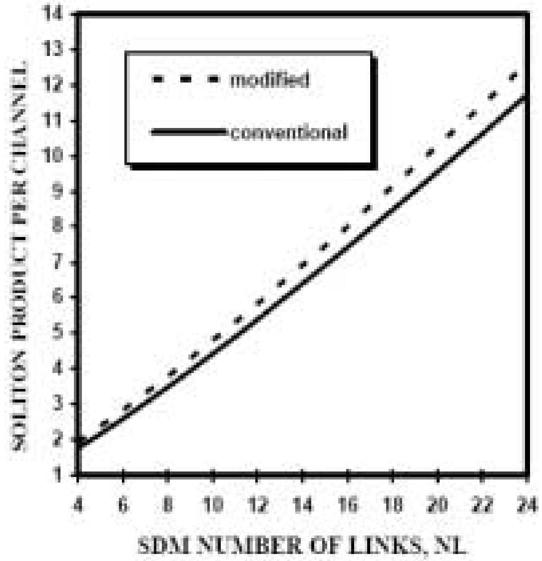


**Fig.9.** Variations of soliton product/channel, Tbit.km/sec against variations of SDM number of links, $N_L$ at the assumed set of parameters

| | |
|---|---|
| R=2.5 μm | $T_o$=290 °k |
| $\lambda_R$=1.45 μ m | $N_c$=2400 channel |

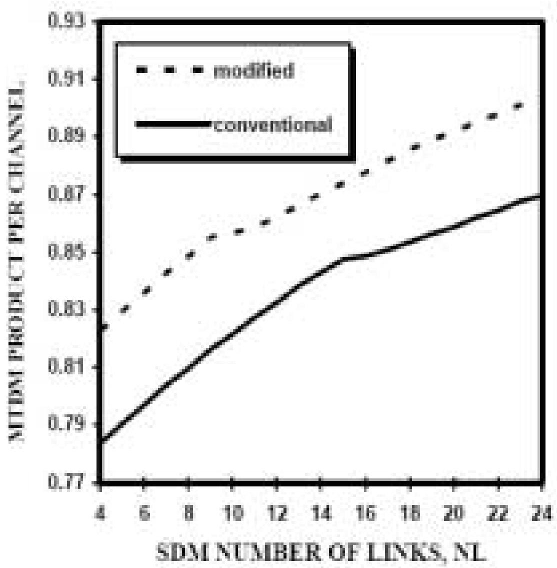


**Fig.10.** Variations of MTDM product/channel, Tbit.km/sec against variations of SDM number of links, $N_L$ at the assumed set of parameters

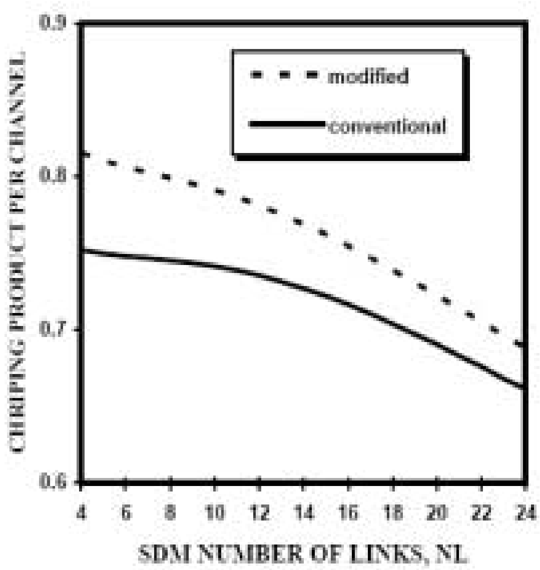


**Fig.11.** Variations of chirping product/channel, Tbit.km/sec against variations of SDM number of links, $N_L$ at the assumed set of parameters

$10^{-5} \le P_W,\ W/THz \le 10^{-3}$

$$k_{ci} = k_o \left[1 - e^{-\sigma_s(\lambda_{si}).L_s}\right] / \sigma_s(\lambda_{si}) \qquad (14)$$

with: $k_o = 1.22 km^{-1}W^{-1}$ : is "Kerr" nonlinear coefficient

$\sigma_s(\lambda_s)$ : is spectral losses in $km^{-1}$. The constant C in Eqn.(13) is given by:

$$C = \left[2\left(\frac{2\pi}{9}\right)^{2/3}\right]^{3/2} = \frac{2\pi}{9}.2^{3/2} = 1.9746$$

The optimal operating power $P_{max,i}$ in W is given by [17,18]:

$$P_{max,i} = \left[\frac{C_p P_W BW_i}{N_s (N_c k_{ci})^2}\right]^{1/3} \qquad (15)$$

where: $C_p = \frac{4\pi^2}{3} = 13.1595$ (dimensionless)

SHP is considered as the ceiling value in present analysis.

## e-Conventional Raman plus parametric amplification

Based on the experimental measurement [11], we cast the following inverted W-shaped combined gain $G_C(\lambda_{Si})$, under the forms:

$$G_C(\lambda_{SI}) = \begin{cases} 100[1.6 + 920(\lambda_{Si} - 1.45)] \\ 1.45 \le \lambda_{SI}, \mu m \le 1.47 \\ \\ 100[20 - 62.5(\lambda_{SI} - 1.47)] \\ 1.47 \le \lambda_{SI} \le 1.545 \\ \\ 100[20 + 50(\lambda_{Si} - 1.625)] \\ 1.545 \le \lambda_{SI} \le 1.625 \\ \\ 100[20 - 500(\lambda_{Si} - 1625)] \\ 1.625 \le \lambda_{Si} \le 1.66 \end{cases} \qquad (16)$$

This gain represent the old one in Eqn. (2) namely $\frac{g_i}{A}P_R$ which is in $m^{-1}$ and $\frac{1000 g_i}{A}P_R$, dB $km^{-1}$

In the performed experiment the length was about 2 km and power $P_R$ = 10 Watt. To obtain:

$$\frac{g_i}{A} = \frac{G_C(\lambda_{si})}{20} \quad km^{-1}W^{-1}$$

$$= 0.05 G_C(\lambda_{si}) \quad km^{-1}W^{-1} = G_{RP}(\lambda_{si}) \qquad (17)$$

Thus( in the presented model we replace $\frac{g_i}{A}P_R$ in $m^{-1}$ by $\frac{G_C(\lambda_{si})}{20}P_R$ or $\frac{g_i}{A}P_R$ in $m^{-1}$ by 0.05 $G_C(\lambda_{Si})P_R$ in $km^{-1}$

## 3. Results and Discussion

In the present paper, we investigate five basic technique to transmit 2400 UDWDM wavelengths in the interval of 1.45 up to 1.65 μm. The five techniques are:

a) "Shannon" capacity
b) Chirped pulses propagation
c) Soliton propagation with conventional Raman amplifier plus EDFA.
d) Soliton propagation with modified Raman amplifier by parametric effect plus EDFA
e) MTDM propagation

For the reality from the points of view of the spectral dependencies of the different fiber characteristics, we employ also the SDM where the 2400 channels are divided into subgroups each subgroup has its own spectral characteristics. Two amplification techniques (distributed "Raman" plus EDFA) are employed to increase the repeater spacing $z_R$. Lucent "AllWave" fiber [10] is used plus the using of dispersion managed fiber (DMF) through alternative dispersions pairs of sections $N_o$ and the chirped pulses to decrease the pulse width and consequently increases the repeater spacing $z_R$ and consequently reduces the repeater spacing per section. Real exact analysis is employed where each channel has its own spectral characteristics (losses, dispersion, and amplification parameters). The available transmitted bit-rates are $B_{sh}$ $B_{rsi}$, $B_{rmi}$, and $B_{rci}$ are computed as well as the repeater spacing $z_{iR}$ and consequently the product $\prod_{ri}$ is computed as:

$$\Pi_{ri} = B_{ri}.z_{iR} \qquad (18)$$

To obtain an order-of-magnitude estimate, and good feeling of the obtained variations via the total value of $\prod_{ri}$ over different SDM groups where, we have:

$$\Pi_{sh} = shp \qquad (19)$$

$$\Pi_c = \sum_{i=1}^{N} \Pi_{rci} \qquad (20)$$

$$\Pi_s = \sum_{i=1}^{N} \Pi_{rsi} \qquad (21)$$

$$\Pi_m = \sum_{i=1}^{N} \Pi_{rmi} \qquad (22)$$

where $\prod_{sh}$, $\prod_c$, $\prod_s$, and $\prod_m$, are the total products of $N_C$ channels divided into subgroups, space division multiplexing SDM due to "Shannon", chirped pulse, solitons, and MTDM ( for conventional and modified Raman) respectively and $\prod_{rci}$, $\prod_{rsi}$ and $\prod_{rmi}$ are the individual product of the i-th. channel.

The employed ranges of variables are as follows:

R = fiber radius = 2.5 μm, $1.45 \le \lambda_{si}, \mu m \le 1.65$, $N_C \le 2400$ channels, $0.0 \le x, \% \le 0.25$, $N_L$={4,5,6,7,…….,24} links,

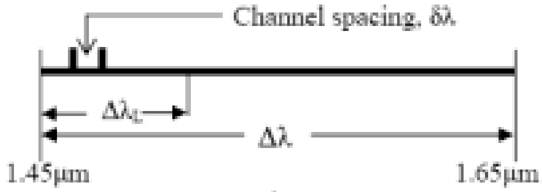


Fig.1

$\Delta\lambda_L = \Delta\lambda / N_L$ = Link spectral spacing

$\Delta\lambda = \lambda_f - \lambda_i = 1.65 - 1.45 = 0.2$ μm

δλ, channel spacing, $= \frac{\Delta\lambda}{N_c} = \frac{0.2}{N_c}$, μm,

$290 \le T, {}^oK \le 300$, $1.0 \le P_R$, Watt $\le 1.5$,

$0.002 \le \Delta n \le 0.008$, and $0.2 \le P_{sio}$, mW $\le 3.0$

The designed data for each link of the $N_c$ links in the SDM channels has its own characteristics of the set of values {x, Δn, $P_{sio}$, $P_{Ro}$ } as given below:

$\Delta x = x_f - x_i = 0.25 - 0.0 = 0.25$

$\Delta n = \Delta n_f - \Delta n_i = 0.008 - 0.002 = 0.006$

$\Delta x_{ch} = \frac{0.25}{2400}$, $\Delta n_{ch} = \frac{0.006}{2400}$

$$x_L / \text{link}(J_L) = x_i + (J_L - 1)\Delta x_{ch}.N_c / N_L \quad (23)$$

$$\Delta n_L / \text{link}(J_L) = \Delta n_i + (J_L - 1)\Delta n_{ch}.N_c / N_L \quad (24)$$

$$\lambda_i / \text{link}(J_L) = \lambda_i + (J_L - 1)\Delta\lambda_{ch}.N_c / N_L \quad (25)$$

$$\lambda_{ave}(\text{link } J_L) = \lambda_i / \text{link} + 0.5 N_c / N_L.\Delta\lambda_{ch} \quad (26)$$

where the suffex f denotes the final value and i denotes the initial value $J_L$ is the order of link and $\lambda_{ave}$(link ($J_L$) is the average wavelength over the link of order $J_L$

$$P_{so}(N_L) = \frac{500}{(N_c / N_L)^2.\Delta f}, \text{ Watt} \quad (27)$$

where Δx is the range of variations of x , δn is the incremental range of variations of Δn, $J_L$ is the order of link where $1 \le J_L \le N_L$ ,$N_L$ is the total number of links, $\lambda_{si}$ is the initial wavelength at the link $J_L$, and $\lambda_{sf}$ is the final wavelength at the link $J_L$

Figure 2. indicate the increase of repeater spacing with increase of the SDM number of links

The variations of $\prod_{sh}$ $\prod_c$ ,$\prod_s$ and $\prod_m$ against the variations of SDM links, $N_L$ and the set of controlling parameter are displayed in Figs.(3-6, 8-11), where the following facts are assured:

i) As the number of links $N_L$ increases, $Z_r$ increases.
ii) Shannon product is the ceiling then the soliton product, Chirping product, and finally MTDM product.
iii) All the products possess higher values in the case of modified Raman gain.
iv) MTDM product and $N_L$ are in positive correlation.
v) The average value of the total dispersion coefficient $D_{t,ave}$ is about –0.7 psec/km.nm different ranges of operation of the two controlling parameters $\Delta x = x_f - x_i$ and $\Delta n = \Delta n_f - \Delta n_i$ are of impact to reduce $D_{t,ave}$ yielding higher products.

Figure 7. indicate of the average power of the signal/link with increase SDM number of link

## 4. Conclusions

A rigorous investigation of UDWDM with the aid of SDM is carried out deeply and parametrically, where 2400 channels over the range 1.45 →1.65 μm with channel spacing 0.1 nm are multiplexed through “Lucent” “AllWave” fiber. Five real techniques of propagation are processed in order to maximize the transmitted bit-rate as well as two amplification techniques (Raman plus EDFA) to maximize the repeater spacing. The coupling of both the bit-rate and the transmitted distance is considered. DMF is employed. Based on the analysis the following major conclusions are made the modified Raman gain yield higher effects of the variable under consideration if compared and the conventional Raman. The number of links is in positive correlations and the set of effects {Repeater spacing, Soliton product, MTDM product}.

In general Shannon product is the ceiling. The average value of the total dispersion coefficient $D_{t,ave}$ is about –0.7 psec/km.nm. The vital affecting parameters are the total successive sections of alternative dispersions as the design parameters (Δx, Δn) which reduce the total dispersion coefficient.

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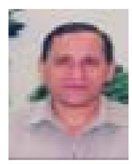

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