Bit Rate Calculation in Multi-Core All Wave Single-Mode Optical Fibers Using Soliton and Nonlinear Transmission Techniques

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Abstract - In the present work, one investigates a dense wavelength division multiplexing (DWDM) system in a multicore optical fiber, i.e. a space division multiplexing (SDM) system. A 1200 different channels in the wavelength range 1450-1650 nm are applied to the fiber. Through controlling the fiber parameters, chromatic dispersion is squeezed at a constant low level. Soliton and nonlinear chirping transmission techniques are employed at different ocean depths. This system has realized a minimum repeater spacing in the range 276-298 km and a corresponding total bit rate for cable in the range 56 Tbps (46.6 GHz per channel)-452 Tbps (376.6 GHz per channel) for soliton transmission and in the range 3.1 Tbps (2.6 GHz per channel) to 5.6 Tbps (4.6 GHz per channel) for nonlinear chirping transmission.

I. INTRODUCTION

The attractiveness of light wave communications is the ability of silica optical fibers to carry large amounts of information over a long repeaterless span. One of the most powerful techniques in optical fiber communication systems is wavelength division multiplexing (WDM). By utilizing the large (~200 nm), low-loss (0.2–0.4 dB/km) transmission bandwidth, a single fiber can potentially support the transmission of tens of terabits per second of information over thousands of kilometers to meet the exponentially-growing capacity demand. One of the key components for WDM systems is the optical amplifier. Currently, the most widely used one is the erbium-doped fiber amplifier (EDFA). However, its bandwidth and operating wavelength are limited and can be extended from 1530 nm to 1605nm [1]. More over, EDFA suffers from fiber transmission loss resulting in noise accumulation and also from nonlinearity that causes signal distortion and noise generation.

In contrast with this, Raman amplifiers were structured as a distributed type which can use ordinary transmission fibers as a gain medium advantageously less susceptible to noise accumulation and thus are more capable of avoiding nonlinearity effects. By broadening the bandwidth of the pump, the gain could be broadened in away not achievable with EDFAs [2] making themselves indispensable for the next-generation transmission systems. While one of the most promising candidates to EDFA is the fiber optical parametric amplifier (OPA). Parametric amplifiers have the potential to achieve wide bandwidth, flat gain, and applications at both 1.3 μm and 1.55 μm [3]. Recent research suggests that an optimum system can be configured using Raman gain in combination with EDFAs, where the transmission capacity is expected to be improved by as much as several to 10 times compare to those where only EDFA is used. Such System would require a fiber that has clear transmission with low loss continuity from 1300nm to 1600 nm instead of the present conventional fiber that has a peak loss at 1380 nm [4]. AllWave fiber reduced the attenuation caused by OH- group by removing it during the course of fiber manufacturing Thus, the fiber can be used over a wide wavelength band of 1280 nm to 1625 nm [5]. Not only does AllWave provide more wavelengths, but also the added wavelengths near 1400nm are in an optimum dispersion region for economically carrying high-speed (10 Gb/s) signals. In the present work, a combination of a parametric and a Raman gain amplifiers [6] in conjugation with an EDFA is investigated. Slotted core AllWave single mode optical fibers are used in a WDM system. Soliton and nonlinear chirping are taken as a sample of two transmission techniques to calculate the maximum repeater spacing and maximum bit rate that can be realized at squeezed chromatic dispersion over all the cores in a slotted multi-core cable.

II. BASIC MODEL AND ANALYSIS

The most important parameter that affects the bit rate is the chromatic dispersion. For single-mode fibers, it is given by [7]:

$$D_t = D_m + D_w \quad (1)$$

where D_m is the material dispersion, which, for three orders of dispersion, is defined by [7]:

$$D_m = \frac{-\lambda}{c} n'(\lambda,T,P) - \frac{\Delta\lambda}{2c}(\lambda n''(\lambda,T,P) + n'(\lambda,T,P)) - \frac{(\Delta\lambda)^2}{6c}(\lambda n'''(\lambda,T,P) + 2n''(\lambda,T,P)). \quad (2)$$

and D_w is the waveguide dispersion is given by [7]:

$$D_w = \frac{n - n_{cl}}{\lambda c} V \frac{d^2(Vb)}{dV^2}, \quad (3)$$

where n, n_{cl} are core and cladding refractive indices respectively, λ is the signal wavelength, V is the normalized frequency and b is the normalized propagation constant.

Based on Refs. [3, 8 and 9] which define the three terms Sellmeier equation for the refractive index of silica glass and its temperature and pressure dependence (or, ocean depth dependence), one can get both D_m and D_w and consequently D_t.

Forward Raman amplification

In a WDM system of N_c channels per core, with a channel spacing Δf in GHz, the power per channel, p in W, has to satisfy the limitation [10]:

$$p_s = \frac{500}{N_c(N_c-1)\Delta f}\ \text{GHz.} \tag{4}$$

In forward Raman amplification for a transmission distance z, the signal power, p_{si} (i=1, 2, ..N_c) and the pump power, p_R are governed by the two nonlinear differential equations [11 and 12]:

$$\frac{dp_{si}(z)}{dz} + \alpha_{si} p_{si}(z) = (\frac{g_i}{A_i} p_R(z) + \frac{\sum_{j=1}^{i-1} g_i p_{sj}(z)}{A_i} - \sum_{m=i+1}^{N} \frac{\lambda_{m}}{\lambda_i}\frac{g_{im} p_{sm}(z)}{A_i}) p_{si}(z) \ , \tag{5}$$

$i = 1, 2, ... N_c$

and

$$\frac{dp_R(z)}{dz} + \alpha_R p_R(z) = -\sum_{i=1}^{N_c} \frac{\lambda_{si}}{\lambda_R}\frac{g_i p_{si}(z)}{A_i} p_{si}(z) p_R(z) \tag{6}$$

where λ_{si} , λ_R are signal and Raman wavelengths, respectively g_i is the Raman gain constant coupling the pump and the ith signal, g_{ij} is the gain constant coupling the ith and jth signal channels, A_i is the effective core area and α is the attenuation coefficient.

Solving Eqs.(5 and 6), the signal power at a distance z can be obtained as:

$$p_{si}(z) = \frac{k e^{-\sigma_{si} z}}{1 + (\frac{k}{p_{so}} - 1) e^{-\frac{ca}{\sigma_{si}}(1 - e^{\sigma_{si} z})}} \ , \tag{7}$$

where

$$a = \frac{g_{ij}}{A_i} \ , \tag{8}$$

$$c = p_{Ro} + \sum_{i=1}^{N} \frac{\lambda_i}{\lambda_R} p_{so} \ , \tag{9}$$

$$k = \frac{ac}{a\sum_{i=1}^{N_c} \frac{\lambda_{si}}{\lambda_p} - \sum_{j=1}^{i-1} \frac{g_{ij}}{A_i} + \sum_{m=i+1}^{N_c} \frac{\lambda_m g_{im}}{\lambda_{si} A_i}} \ . \tag{10}$$

$i = 1, 2 .. N_c$

where p_{so} is the initial signal power at $z = 0$, has to satisfy Eq.(7), p_{Ro} is Raman input power. In the proposed system P_{Ro} = 1.5 W. Based on the experimental data reported in [6], we have tailored the combined gain of Raman and optical parametric amplifier over the wavelength range 1.45 - 1.65 μm.

EDFA Gain

The signal power, $p_{si}(z)$, increases firstly due to Raman amplification, and then it begins to decrease till its value downs to the amplified spontaneous emission (ASE) level. At this distance EDFA raises the again by 30 dB. Thus the signal level is 10^3 times the ASE. Consequently, the repeater spacing increases again to a longer distance at which the signal power reaches again the ASE level.

In the present work, one investigates the repeater spacing of multi-core undersea optical fiber cable under various depths .This distance is employed in calculating the system bit rate for two transmission techniques, soliton and nonlinear chirping. The gain dependence in temperature is obtained from the model described in Ref. [13].

Loss Calculation

Taking into account the effect of the refractive index differenceΔ, the tailored formula for the AllWave fiber loss, σ_i , is given by [12]:

$$\sigma_i = [0.19 + 7.04(\lambda - 1.55) + 34.06(\lambda - 1.55)^3 + 72.11(\lambda - 1.55)^4 + 36.7(\lambda - 1.55)^5]\alpha_T + 7\Delta + \sigma_{IS}, \tag{11}$$

where α_T $(= \sigma_{tc}(\lambda, T)/\sigma_{tc}(\lambda))$ is the thermal loss, σ_{tc} is the theoretical loss in the conventional single mode fiber, and σ_{IS} is the intrinsic loss taken in the model by 0.03.

Bit Rate Calculations

i) Soliton technique

The soliton bit rate B_{rsi} is a distance free quantity. It is given [14] as:

$$\frac{p_{sio}}{B_{rsi}^2} = 59.7(\frac{\lambda_{si}}{1.45})^3(\frac{A}{20})(\frac{3.2\times10^{-20}}{n_2})|D_t| \ , \tag{12}$$

where, p_{sio} is the initial pulse power for the i-th channel.

Under the limitation of Eq(4).

ii) Nonlinear chirping technique

The pulse width in the nonlinear chirping is reduced to the initial chirp and is given by [15]:

$$\tau_c = \tau_{co}(\sqrt{1 + 0.543 v(z - z_o)^2} - a_o) \ , \tag{13}$$

where

$$a_o = \sqrt{1 + 0.543 v z_0^2} - 1 \ , \tag{14}$$

$$z_o = c_o(-2\pi\alpha_f \frac{p_{so} n_2}{\lambda A_{eff}})^{-1} \ , \tag{15}$$

$$v = -\frac{p_{so}\lambda n_2 D}{c t_o^2 A_{eff}} a_f \quad . \tag{16}$$

and τ_{co}, τ_c are the initial and final chirped pulse width. z_o is the propagation distance at the initial chirp. a_f is the form factor, D_t is the dispersion parameter and n_2 is the non-linear refractive index coefficient for pure Silica, n_2 as a function of the germania doping is given experimentally in [14] and we cast it as:

$$n_2 = 3.2\times10^{-19}\,(1 + 2.81294\,x - 16.6123\,x^2 + 459808\,x^3), \tag{17}$$

Chirping bit rate calculations are carried out at the average bit rate for different chirped pulse (hyperbolic, secant, Guassian, super Guassian, Lorentzian, parabolic, triangular and exponential cusp) [15]. In this technique the initial chirp reduces the chromatic dispersion coefficient, D_t, and, consequently, it reduces the rms pulse broadening and gives the chirped bit rate of the i-th channel B_{ci} as:

$$B_{ci} = 1/4\tau_c \quad . \tag{18}$$

III. RESULTS AND DISCUSSION

Using the explained model, we have applied a number of 1200 channels in the band 1450 to 1650 nm in multi core optical fiber cable (SDM). The total number of cores taken is, NC = 10, 20…..80. The chromatic dispersion in all the cores in the slotted cable are sustained at constant level (D_t = - 0.1 ps/nm.km.) by controlling the values of Δ and x, the germania doping mole fraction, keeping fiber radius, a, central source wavelength, λ, and source spectral width, $\Delta\lambda$, constant. This investigation was done at various environmental conditions in terms of fiber temperature and fiber pressure which are combined in one variable, ocean depth [16]. We display now a sample of results for the repeater spacing and the bit rate in both soliton and nonlinear chirping transmission techniques.

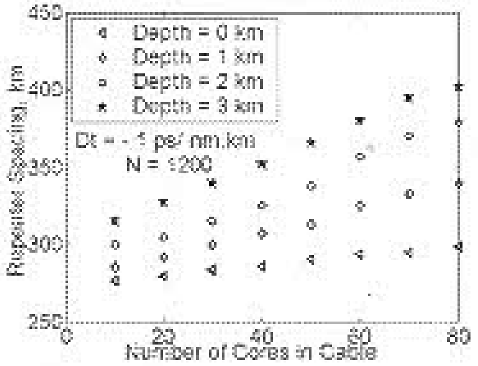

Fig.1 Repeater spacing versus number of cores at various depths

Figure 1 displays the repeater spacing versus the number of cores at different depths showing that, the repeater spacing, R_s, increases with both depth and number of cores. This can be explained by Eq. (11) which states the increase of the fiber loss with the relative refractive index difference, which decreases with depth as shown in Fig.2. It is clear from Eq.(4) that the signal feeding power is increased, due to the reduction in the number of multiplexed signal per core resulting from increasing the number of cores in the cable, resulting in an increase in R_s.

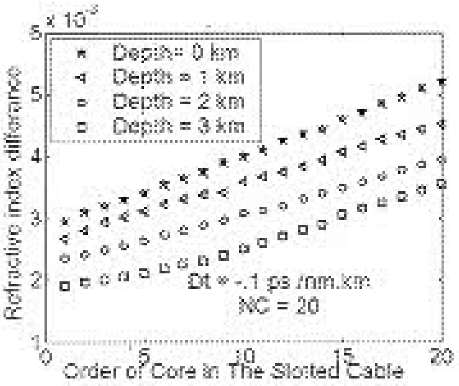

Fig.2 Relative refractive index difference versus the order of the cores in cable at different depths

Figure 3 displays the soliton bit rate against number of cores at different ocean depths, in consistence with Eq.(12). In contrast, Fig.4 shows that the bit rate decreases with the number of cores when the nonlinear chirping is employed. This is expected because the chirped pulse is directly proportional to the feeding power, Eqs.(13 and 15).

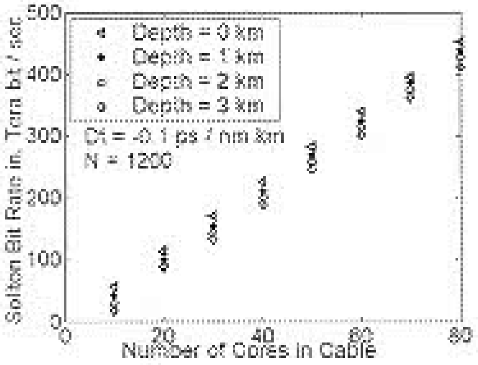

Fig.3 Soliton bit rate versus number of cores in cable at different depths.

A comparison between soliton and nonlinear chirping bit rates is given in Fig.5, from which one can see how the soliton is advantageous concerning its higher bit rate.

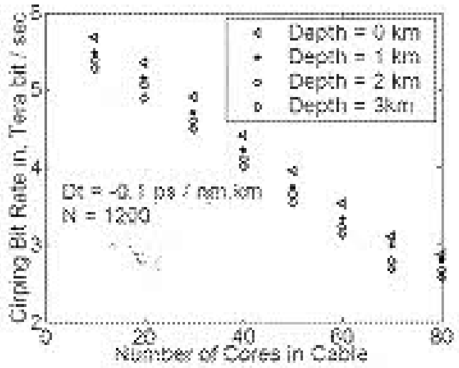

Fig.4 Nonlinear chirping bit rate versus number of cores in cable at different depths

Fig.5 Soliton bit rate and chirping bit rate versus the order of cores in cable

IV. CONCLUSION

Application of SDM and DWDM in soliton transmission systems results in increasing the bit rate with the number of cores. However, applying SDM to nonlinear chirping transmission system, keeping the operating conditions (chromatic dispersion, feeding power and Raman power) the same for all cores leads to a degradation in bit rate. There is a trade of between the maximization of repeater spacing through increasing the input signal power and the bit rate maximization in chirping transmission systems. Repeater spacing is more sensitive to the variation in environmental conditions than the bit rate. Combination between Raman gain and parametric amplifier provides a gain having a W-inverted shape [6] suitable for applying DWDM in the wavelength range 1450-1650 nm. According to the number of cores and the ocean depth., this system has realized a minimum repeater spacing in the range 276-298 km and a corresponding total bit rate for cable in the range 56 Tbps (46.6 GHz per channel)-452 Tbps (376.6 GHz per channel) for soliton transmission and in the range 3.1 Tbps (2.6 GHz per channel) -5.6 Tbps (4.6 GHz per channel) for nonlinear chirping transmission.

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