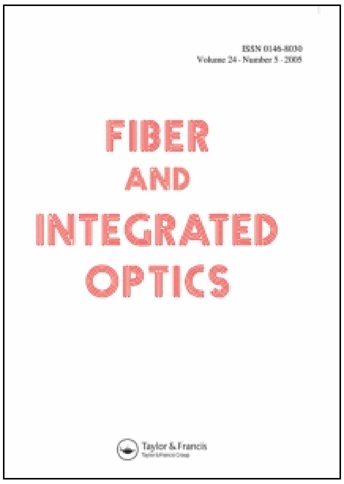

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Large Signal Analysis of FM-AM Conversion in Dispersive Optical Fibers for PCM Systems Including Second Order Dispersion

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By using large signal analysis for dispersive optical fiber, the FM-AM conversion with respect to binary intensity modulated PCM systems including second order dispersion term is discussed. The modified expression for power penalty has been derived and its impact on laser linewidth and bit rate has been investigated. For power penalty less than 0.5 dB, the plots between bit rate and transmission distance are plotted. It is seen that the transmission distance increases with decrease in linewidth over significant bit rates. The transmission distance with first order dispersion term for 300 MHz linewidth is approximately 800km. With proper first order dispersion compensation, i.e., with second order dispersion only, the transmission distance can be enhanced to 10^8 km for this linewidth. The linewidth requirements for systems with different bit rates and transmission distances are also calculated and discussed. Further, it is seen that by including the second-order dispersion term, the bit rate and transmission distance decreases. For higher linewidths, this decrease in bit rate and transmission distance

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is very less and vice versa. For 300 MHz linewidth, the decrease in transmission distance is just 30 km, and for 30 MHz linewidth, the decrease is approximately 600 km over significant bit rates.

Keywords first order and second order dispersion, laser linewidth, power penalty, compensation

Introduction

The invention of the erbium-doped fiber amplifier (EDFA) [1, 2] paved the way for the development of high bit rate all optical ultra long-distance communication systems. Specifically, periodic compensation of fiber loss by EDFAs eliminates the need for electronic repeaters along the transmission line and enables the construction of all-optical communication systems in which the transmission distance is limited by the fiber chromatic dispersion rather than by the fiber loss because it introduces signal distortion and noise [3–8]. However, if conventional 1.3 μm zero-dispersion optical fiber systems and networks are used for the 1.55 μm signal light, they exhibit a significant dispersion yielding, e.g., limitations with respect to transmission bandwidth [9–10]. Different theories [11–13] have been developed in the past to study the propagation of modulated signal produced by semiconductor lasers through dispersive medium. Wedding et al. [11] showed using small signal theory that frequency-modulated optical transmitter at low loss wavelengths have high pass transfer characteristics. Equalizing this frequency response, the characteristics of the receiver low pass filter could be determined that were required for the method of dispersion-supported transmission. Further using the same theory, Chraplyvy et al. [12] measured the induced-amplitude modulation of sinusoidal phase-modulated light signal in a single mode fiber. Amplitude modulation was observed for a phase-modulated wave at 4 GHz, which produced poor penalty in the coherent transmission systems. Wang et al. [13] developed a new approach to investigate the influence of the dispersion on optical fiber communication systems using small signal analysis. A conversion matrix describing the transfer function of intensity and frequency modulation at fiber input to the intensity and frequency modulation at fiber output was reported, and the results were obtained to analyze the performance of optical communication systems. Crognale et al. [14] extended the analysis of Wang to include the second order dispersion term, and results were compared with that of a first-order dispersion term [13].

Peral et al. [15] derived an expression for an exact large signal theory for propagation of an optical wave with sinusoidal amplitude and frequency modulation in a dispersive fiber. This was applied to direct modulation of semiconductor lasers. Peterman et al. [16], using large signal analysis, discussed the FM-AM conversion for a dispersive optical fiber with respect to binary intensity-modulated PCM systems. This was the same type of analysis [13] that limited up to first-order dispersion term only; the second-order dispersion term was ignored. In this paper, we extend the analysis for large signal theory [16] by including the second-order dispersion term to study the FM-AM conversion for a dispersive optical fiber with respect to binary intensity-modulated PCM systems, as was done by Crognale et al. [14] for small signal analysis.

Theory

We consider a single mode fiber transmission line; at the fiber input we have a complex input field,

$$E_a(t) = E_{in}(t)e^{j\omega_o t}, \tag{1}$$

with the slowly varying complex amplitude $E_{in}(t)$ and the mean optical frequency ω_o. This input field will be transferred to the output field,

$$E_b(t) = E_{out}(t)e^{j\omega_o t}, \tag{2}$$

with the slowly varying complex field amplitude $E_{out}(t)$ at the fiber output. The propagation of a signal through an optical fiber can be described in terms of propagation constant β by the equation described in terms of a Fourier transform as

$$E_{out}(\omega) = E_{in}(\omega)e^{-j\beta L}, \tag{3}$$

where the propagation constant in terms of Taylor series can be expanded as

$$\beta = \beta_o + (\omega - \omega_o)\frac{d\beta}{d\omega} + \frac{1}{2}(\omega - \omega_o)^2\frac{d^2\beta}{d\omega^2} + \frac{1}{6}(\omega - \omega_o)^3\frac{d^3\beta}{d\omega^3}\cdots, \tag{4}$$

where $\frac{d\beta}{d\omega} = \tau$ is the group delay for unit length

$$\beta = \beta_o + (\omega - \omega_o)\tau + \frac{1}{2}(\omega - \omega_o)^2\frac{d\tau}{d\omega} + \frac{1}{6}(\omega - \omega_o)^3\frac{d^2\tau}{d\omega^2}\cdots, \tag{5}$$

$$\frac{d\tau}{d\omega} = -\frac{\lambda^2}{2\pi c}\frac{\partial\tau}{\partial\lambda} \tag{6}$$

is first order dispersion, and

$$\frac{d^2\tau}{d\omega^2} = \frac{\lambda^2}{(2\pi c)^2}\left[\lambda^2\frac{\partial^2\tau}{\partial\lambda^2} + 2\lambda\frac{\partial\tau}{\partial\lambda}\right] \tag{7}$$

is second order dispersion.

Recalling eq. (3) the following expression is obtained for propagation constant term

$$e^{-j\beta L} = e^{-j\beta_o L - jL(\omega-\omega_o)\tau - jL\frac{1}{2}(\omega-\omega_o)^2\frac{\partial\tau}{\partial\omega} - jL\frac{1}{6}(\omega-\omega_o)^3\frac{\partial^2\tau}{\partial\omega^2} - \cdots}, \tag{8}$$

where $\phi_o = \beta_o L$ at $\omega = \omega_o$. As reported [13–16], we neglect the phase and group delay ($\phi_o = \beta_o L$ and $\frac{d\beta}{d\omega} = \tau$) because both terms produce only phase delay of the carrier signal and have no influence on the distortion of the signal. We define the following dispersion parameters

$$F_2 = -\frac{L}{2}\frac{d\tau}{d\omega} = \frac{L}{2}\frac{\lambda^2}{2\pi c}\frac{\partial\tau}{\partial\lambda}, \tag{9}$$

$$F_3 = \frac{L}{6}\frac{d^2\tau}{d\omega^2} = \frac{L}{6}\frac{\lambda^2}{(2\pi c)^2}\left[\lambda^2\frac{\partial^2\tau}{\partial\lambda^2} + 2\lambda\frac{\partial\tau}{\partial\lambda}\right]. \tag{10}$$

We rewrite the output equation in terms of Fourier domain as

$$E_{out}(\omega) = e^{(j(\omega-\omega_o)^2F_2 - j(\omega-\omega_o)^3F_3\cdots)}E_{in}(\omega). \tag{11}$$

In time domain

$$\left(j\omega = \frac{\partial}{\partial t}\right), \left((j\omega)^2 = -\omega^2 = \frac{\partial^2}{\partial t^2}\right), \text{ and } \left((j\omega)^3 = -j\omega^3 = \frac{\partial^3}{\partial t^3}\right)$$

$$E_{out}(t) = e^{(-jF_2\frac{\partial^2}{\partial t^2} + F_3\frac{\partial^3}{\partial t^3}\cdots)} E_{in}(t). \tag{12}$$

The input field amplitude may be written as

$$E_{in}(t) = \sqrt{P(t)}e^{j\phi(t)}, \tag{13}$$

with the phase $\phi(t)$ and optical power $P(t)$. Inserting eq. (13) in eq. (12),

$$E_{out}(t) = e^{(-jF_2\frac{\partial^2}{\partial t^2} + F_3\frac{\partial^3}{\partial t^3}\cdots)} \sqrt{P(t)}e^{j\phi(t)}, \tag{14}$$

$$E_{out}(t) = E_{in}(t) + \Delta E(t), \tag{15}$$

where $|\Delta E(t)| \ll |E_{in}(t)|$.

From eq. (14) and (15),

$$\Delta E(t) = (e^{(-jF_2\frac{\partial^2}{\partial t^2} + F_3\frac{\partial^3}{\partial t^3}\cdots)} - 1)\sqrt{P(t)}e^{j\phi(t)}, \tag{16}$$

$$P_{out}(t) = |E_{in}(t) + \Delta E(t)|^2 \approx |E_{in}(t)|^2 + 2\Re[E_{in}^*(t)\Delta E(t)]. \tag{17}$$

Substituting eq. (13) and eq. (16) in eq. (17),

$$P_{out}(t) = P + 2\Re[\sqrt{P(t)}e^{-j\phi(t)}(e^{(-jF_2\frac{\partial^2}{\partial t^2} + F_3\frac{\partial^3}{\partial t^3}\cdots)} - 1)\sqrt{P(t)}e^{j\phi(t)}]. \tag{18}$$

Expressing $e^x = 1 + x$ (the expansion has been carried out only up to first term because for PCM transmission, the spectrum due to noise is considered to be narrow), we get

$$P_{out}(t) = P + 2\Re\left[\sqrt{P(t)}e^{-j\phi(t)}\left(-jF_2\frac{\partial^2}{\partial t^2} + F_3\frac{\partial^3}{\partial t^3}\cdots\right)\sqrt{P(t)}e^{j\phi(t)}\right], \tag{19}$$

$$\begin{aligned} P_{out}(t) = P &+ 2\Re\left[\sqrt{P(t)}e^{-j\phi(t)}\left(-jF_2\frac{\partial^2}{\partial t^2}\sqrt{P(t)}e^{j\phi(t)}\right)\right] \\ &+ 2\Re\left[\sqrt{P(t)}e^{-j\phi(t)}\left(jF_3\frac{\partial^3}{\partial t^3}\sqrt{P(t)}e^{j\phi(t)}\right)\right], \end{aligned} \tag{20}$$

$$P_{out}(t) = P + A + B, \tag{21}$$

where A and B correspond to first and second real parts in eq. (20):

$$A = 2F_2\frac{d}{dt}(P\phi') = 2F_2P\phi'' + 2F_2\phi'\frac{dP}{dt}, \tag{22}$$

$$\begin{aligned} B = 2F_3\Bigg[&-\frac{dP}{dt}(\phi')^2 - 3P(\phi')(\phi'') - \frac{1}{2}\frac{dP}{dt}(\phi')^2 + \frac{1}{2}\frac{d^3P}{dt^3}(\phi')^2 \\ &- \frac{3}{4P}\left(\frac{dP}{dt}\right)\left(\frac{d^2P}{dt^2}\right) + \frac{3}{8P^2}\left(\frac{dP}{dt}\right)^3\Bigg], \end{aligned} \tag{23}$$

where $\phi' = \frac{d\phi}{dt}$ and $\phi'' = \frac{d^2\phi}{dt^2}$. For studying the transmission of PCM signals, we consider a sequence 101010 ... sequence represented as

$$P = P_o[1 + \cos(\pi Bt)], \tag{24}$$

where B is the bit rate. We assume chirp-free modulation is obtained by using external modulators. Thus for $\Delta P = A + B$, at the decision point, we have $\frac{dP}{dt} = 0$ for both '1' and '0.' Because $P = 0$ for the space signal, there is noise ΔP only for the marl '1' signal. ΔP is expressed as

$$\Delta P = 2P_o(2F_2\phi'' - 3F_3\phi''\phi'), \tag{25}$$

$$\langle \Delta P^2 \rangle = 4P_o^2(2F_2\phi'' - 3F_3\phi''\phi')^2, \tag{26}$$

$$\frac{\langle \Delta P^2 \rangle}{P_o^2} = 16F_2^2\langle(\phi'')^2\rangle + 36F_3^2\langle(\phi'')^2\rangle\langle(\phi')^2\rangle - 48F_2F_3\langle(\phi'')^2\rangle\langle(\phi')\rangle. \tag{27}$$

$\langle \Delta P^2 \rangle$ represents noise due to FM–AM conversion at the fiber output. The power penalty as expressed in [17, 18] is

$$PP = -5\log_{10}\left(1 - Q^2\frac{\langle \Delta P^2 \rangle}{P_o^2}\right). \tag{28}$$

The spectral power density is given by [19]

$$W_\phi = 2\pi\Delta v. \tag{29}$$

The frequency fluctuations are characterized by spectral power density:

$$\phi' = W_\phi = 2\pi\Delta v, \tag{30}$$

we obtain

$$\langle(\phi')^2\rangle = \int_{-B/2}^{B/2} W_\phi df, \tag{31}$$

$$\langle(\phi')^2\rangle = 2\pi\Delta vB. \tag{32}$$

Also the spectral power density for second derivative of frequency is given by

$$\phi'' = \frac{d\phi'}{dt} = (2\pi f)^2 W_\phi, \tag{33}$$

we obtain

$$\langle(\phi'')^2\rangle = \left\langle\left(\frac{d\phi'}{dt}\right)^2\right\rangle = \int_{-B/2}^{B/2}(2\pi f)^2 W_\phi df, \tag{34}$$

$$\langle(\phi'')^2\rangle = \frac{2}{3}\pi^3\Delta vB^3. \tag{35}$$

Substituting eqs. (30), (32), and (35) in eq. (27) and finally in eq. (28), we get

$$PP = -5\log_{10}\left(1 - Q^2\left(\frac{32}{3}F_2^2\pi^3\Delta v B^3 + \frac{144}{3}F_3^2\pi^4\Delta v^2 B^4 - \frac{192}{3}F_2F_3\pi^4\Delta v^2 B^3\right)\right), \tag{36}$$

so that

$$\frac{\langle \Delta P^2\rangle}{P_o^2} = \frac{32}{3}F_2^2\pi^3\Delta v B^3 + \frac{144}{3}F_3^2\pi^4\Delta v^2 B^4 - \frac{192}{3}F_2F_3\pi^4\Delta v^2 B^3. \tag{37}$$

Results and Discussions

For system penalty to be less than 0.5dB and for $Q = 6$ (corresponding to 10^{-9} bit error rate),

$$\frac{\langle \Delta P^2\rangle}{P_o^2} \leq \frac{1}{175} = \frac{32}{3}F_2^2\pi^3\Delta v B^3 + \frac{144}{3}F_3^2\pi^4\Delta v^2 B^4 - \frac{192}{3}F_2F_3\pi^4\Delta v^2 B^3. \tag{38}$$

Referring to ITU-T Rec. 653 recommendation [20], we assume $\lambda_o = 1.55\ \mu$m, $\frac{\partial\tau}{\partial\lambda} = 20$ *ps/nm.km*, and $\frac{\partial^2\tau}{\partial\lambda^2} = 0.085$ *ps/nm²km*. We obtain following dispersion parameters using equations (9) and (10):

$$F_2 = 12.75x10^{-24}L/km$$

$$F_3 = 2.955x10^{-38}L/km.$$

The Δv maximum linewidth limit can be obtained from eq. (38), where the ratio can be considered to be varying from $5.25x10^{-3}$ to $6x10^{-3}$ for power penalty less than 0.5dB as shown in Figure 1.

In this range the linewidth is calculated to be varying between 10 MHz to 11.3 MHz for the combined case of first and second order dispersion for 10 GHz bit rate with 100 km transmission distance. For 40 GHz bit rate and 300-km transmission distance, the linewidth requirement becomes very narrow, ranging from 17 KHz to 20 kHz. If the system is dispersion-compensated, i.e., if we ignore the first-order dispersion for 1Tb/s bit rate and 1000 km transmission distance, the linewidth requirement is of the order of 1 MHz, which is appreciably high as compared to combined case. For 100 Gb/s bit rate and 1000-km transmission distance, the linewidth is of the order of 1000 GHz for this case. The exact linewidth requirement depends on the modulation format at the transmitter, the transmitted bit rate, and demodulation technique at the receiver. For synchronous detection, the linewidth requirements are not so narrow, and an ordinary laser will be able to work. But for asynchronous detection, less linewidth requirement is placed on the systems at high bit rates and transmission distance. To achieve such narrow linewidth, one needs single longitudinal-mode devices such as a quarter-wavelength shifted DFB laser, a distributed-Bragg-reflector laser, or an external cavity laser.

The plot between bit rate and transmission distance for F_2 only is shown in Figure 2. It is clear that the bit rate decreases with distance. For different linewidth of laser source, as the linewidth decreases, the curve shifts upward indicating the distance enhancement for significant high bit rates. The modulation limit resulting in FM-AM conversion is a function of linewidth. The plot between bit rate and transmission distance for F_3 only is

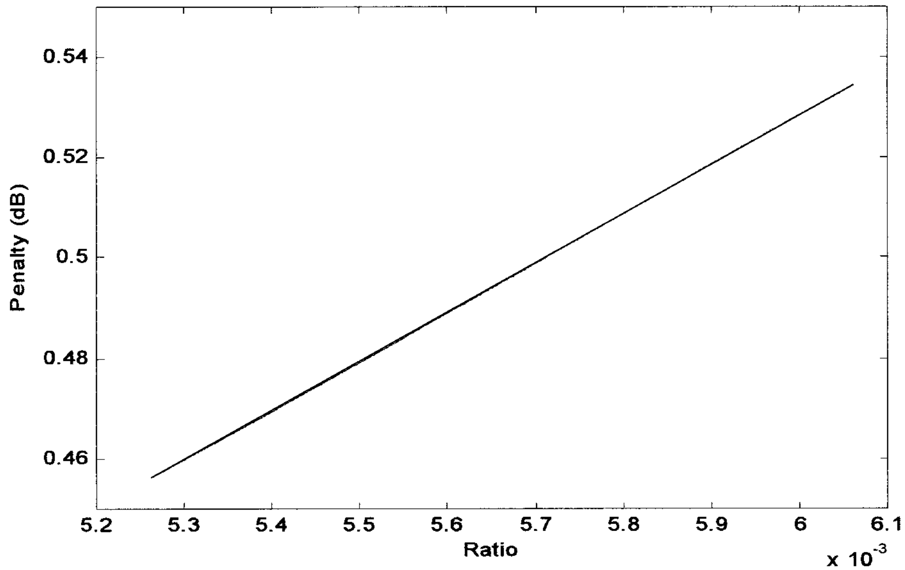

Figure 1. Power penalty versus ratio.

shown in Figure 3. The bit rate decreases with distance as shown in the figure. As the laser linewidth decreases, the curve shifts upward indicating the distance enhancement over significant high bit rates. The further decrease in linewidth will result in the case of modulation limit, resulting in FM-AM conversion limit. The significant point that is noted here is that with F_2 only, the transmission distance for 300 MHz linewidth is 800km, and if F_2 is compensated and only F_3 is taken into account, the transmission distance can

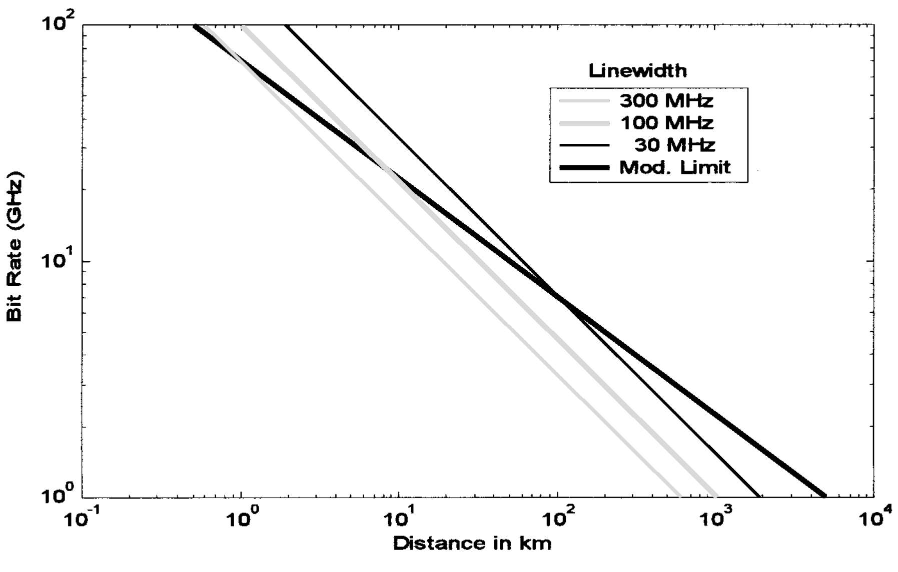

Figure 2. Bit rate versus distance for various values of linewidths for F2.

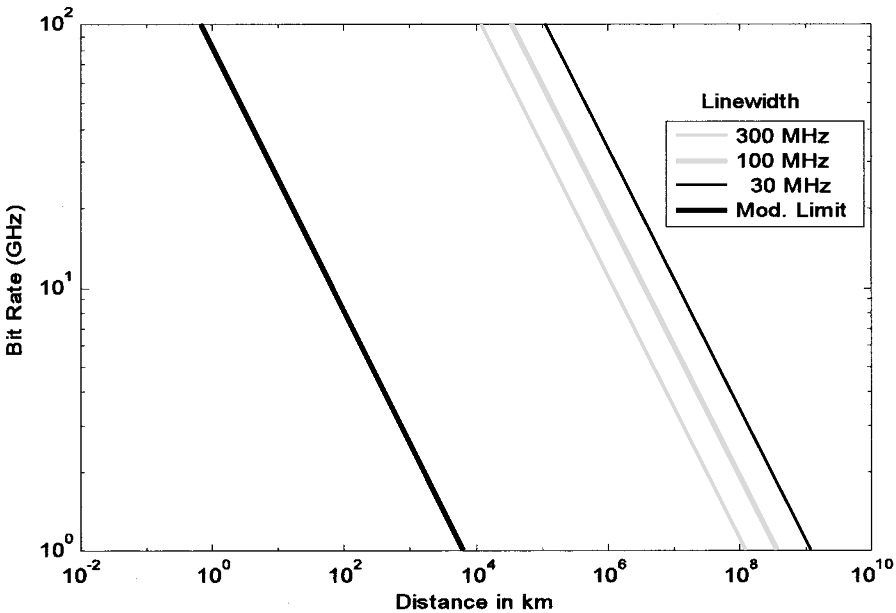

Figure 3. Bit rate versus distance for various values of linewidths for only F3.

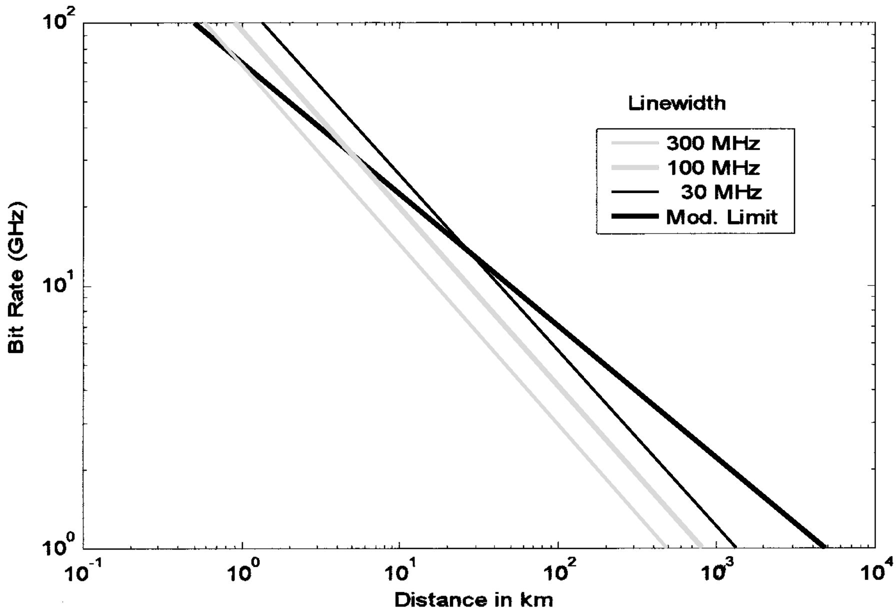

Figure 4. Bit rate versus distance for various values of linewidths for F2 and F3 together.

be enhanced to 10^8 km. The graph for combined case is shown in Figure 4. It is clear that by including the second-order dispersion term, the bit rate and transmission distance decreases. For higher linewidths, this decrease is much less and as the linewidth decreases, the decrease increases. For example, for 300 MHz linewidth, the decrease in transmission distance is just 30 km, and for 30 MHz linewidth the decrease is approximately 600 km over significant bit rates.

In addition, there is usual modulation-induced spectral broadening dispersion limit, which is given by $B\sqrt{F_1} = 0.25$ or $B\sqrt{L_1} = 70Gb/s\sqrt{km}$ [21]. This is modulation limit which signifies the FM-AM noise conversion limit is well coincident with our plots as shown in Figures 2, 3, and 4.

Conclusions

The modified expression for power penalty has been derived and its impact on laser linewidth and bit rate has been investigated. For power penalty less than 0.5 dB, the plots between bit rate and transmission distance are plotted. It is seen that the transmission distance over significant bit rate with a first-order dispersion term is approximately 800km for 300MHz linewidth. With a second-order dispersion only (first-order dispersion term compensated), the transmission distance can be enhanced to 10^8km for this linewidth. The linewidth is calculated at different bit rates and transmission distances, and feasibility for different lasers is also discussed. It is also seen that there is significant change in the transmission distance and bit rate for combined case of first- and second-order dispersion terms together with that of a first-order dispersion term, and this change increases with the decrease in linewidth.

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