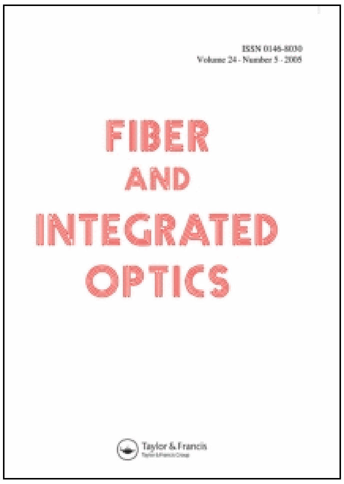

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Theoretical Investigations of Third-Order Dispersion Term on Relative Intensity Noise for Dispersive Optical Communication System

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In this article we present improved theoretical investigations into relative intensity noise (RIN), including the impact of a third-order dispersion term for dispervive optical communication systems. It has been shown that the third-order dispersion term has no impact on RIN even at high noise frequencies as reported by other authors, but with second-order dispersion compensation, the RIN can be dramatically reduced, thereby improving overall system performance. Further, the impact of fiber length and laser linewidth has been investigated for RIN. It has been shown that, as the fiber length increases, the value of RIN increases but the improvement over RIN with second-order dispersion compensation decreases. Also, with decrease in the value of linewidth, the RIN can be reduced to a great extent.

Keywords RIN, dispersion, higher-order dispersion, laser linewidth

Introduction

It is of utmost importance to calculate and compensate for dispersion because this is the physical limitation for high-speed transmission systems resulting from the transmission properties of optical fiber. With the current trends toward ultra-high bit-rate transmission systems, the effect of second- and higher-order dispersion is becoming increasingly significant [1–5]. Even at a constant bias current with negligible current fluctuations, the output light of any semiconductor laser exhibits intensity and phase fluctuations. These fluctuations appear as noise and are particularly detrimental in ultra-fast optical systems

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and networks and act as the fundamental limitation. The dominant process at the origin of these noise phenomena is spontaneous emission. The randomly generated spontaneous light is superposed onto the stimulated emission and thus perturbs both amplitude and phase of the laser. The intensity noise resulting from the phase modulation to intensity modulation conversion of the laser phase can be a major impairment in direct detection systems [6]. The amplitude fluctuation is characterized by relative intensity noise (RIN) [5]. To describe the noise features of any laser diode, it is useful to introduce a RIN parameter relating the intensity fluctuation ΔS to the mean intensity $\langle S \rangle$, RIN referred to a noise bandwidth Δf, relating the intensity fluctuations $\Delta S(\omega)$ to mean intensity $\langle S \rangle$, and given by

$$\frac{RIN}{\Delta f} = \frac{2\langle |\Delta S(\omega)|^2 \rangle}{\langle S \rangle^2}. \tag{1}$$

It is well known that RIN is significantly enhanced after passing through dispersive fiber because of different delays of the spectral components within the spectral width of the laser and because of higher-order dispersion terms.

Petermann [5] showed that considerable FM-AM noise conversion occurs in dispersive fiber links, which must be taken into account when designing analogue subcarrier distribution systems. For a link length of 10 km at $\lambda = 1.55$ μm, RIN values between -125 and -145 dB/Hz are expected for frequencies between 1 and 10 GHz. Further, he showed that for a typical fiber, operated at $\lambda = 1.55$ μm with $d\tau/d\lambda = 20$ ps/km nm, he got $F = 12.75(\text{ps})^2$ L/km, assuming $\Delta\nu = 100$ MHz. The RIN for different link lengths (up to 30 km) was calculated for the second-order dispersion term only.

For AM-VSB system one usually requires at least -150 dB/Hz. For a link length $L = 10$ km, this limit was shown for second-order dispersion term only which exceeded for frequencies over 560 MHz, yielding RIN values in the microwave range at 10 GHz as much as -125 dB/Hz. These RIN values can be reduced either for laser diodes with narrower linewidth or for fiber links with lower dispersion. However, in addition to the FM-AM noise conversion, nonlinear distortion caused by FM-AM conversion must be accounted for in analogue systems.

Cartexo et al. [7] investigated theoretically and experimentally the influence of fiber nonlinearity on the conversion of laser and optical amplifier phase intensity noise by fiber transmission. A very good agreement of RIN spectra at the output of a standard single-mode fiber between experimental data and theoretical prediction was achieved. Results reveal that the fiber nonlinearity and dispersion can enhance significantly the RIN magnitude and lead to a shift of RIN dips toward higher frequencies and consequently to a broader RIN spectrum at the fiber output. The theory presented by them provides a tool to reduce the RIN in cascaded optical amplifiers systems, with suitable choice of system parameters. It may provide basic information to minimize detrimental RIN effects in future communication systems.

Earlier Cartexo and Morgado [8] and Kaler et al. [3] derived an expression for RIN including a higher-order dispersion term using small-signal analysis. It was shown that the third-order dispersion term had a negligible effect on RIN; however, none of them have evaluated RIN for another important parameter: laser linewidth with dispersion compensation.

In this article we extend the results reported in [5] and evaluate RIN including third-order dispersion effects. In the next section we derive a modified expression for RIN, which includes laser linewidth. In the following section we show the effect of dispersion compensation and observe drastic reduction in the RIN in our results. In the final section conclusions have been derived from the plots.

Theory

For the analysis we consider a single-mode laser diode, which exhibits only FM noise, no intensity noise. The complex electric field amplitude from the laser can be written as

$$E_a(t) = E_L(t)e^{j\omega_{th}t}, \tag{2}$$

where ω_{th} is the mean (circular) optical emission frequency, and the slowly varying field amplitude is given as

$$E_L(t) = \sqrt{P_{in}}e^{j\phi(t)}, \tag{3}$$

where P_{in} is the input optical power (assumed here to be constant) and $\phi(t)$ denotes the phase that is exhibiting noise.

The output complex field amplitude can be given as

$$E_b(t) = E_a e^{-j\beta L}, \tag{4}$$

where $E_b(t)$ is the output complex field amplitude, β is the propagation constant, and L is the length of the transmission fiber. The propagation constant β in terms of a Taylor series can be expanded around $\omega = \omega_{th}$ as mentioned in Kaler et al. [1] as

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

where $d\beta/d\omega = \tau$ is the group delay for unit length,

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

is second-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 third-order dispersion.

Recalling Equation (4), we obtain the following expression for a propagation constant term:

$$e^{-j\beta L} = e^{-j(\beta_o+(\omega-\omega_{th})\tau+\frac{1}{2}(\omega-\omega_{th})^2\frac{d\tau}{d\omega}+\frac{1}{6}(\omega-\omega_{th})^3\frac{d^2\tau}{d\omega^2}+\cdots)L}, \tag{8}$$

where $\phi_o = \beta_o L$ at $\omega = \omega_{th}$. As reported in Kaler et al. [1], we neglect the absolute phase and group delay ($\phi_o = \beta_o L$ and $d\beta/d\omega = \tau$) 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:

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

for a second-order dispersion term and

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

for a third-order dispersion term. Now

$$E_b(t) = e^{j(\omega_{th}t-\beta_o L)}e^{[\frac{j}{2}L\frac{d\tau}{d\omega}\frac{d^2}{dt^2}+\frac{L}{6}\frac{d^2\tau}{d\omega^2}\frac{d^3}{dt^3}+\cdots]}E_L(t-\tau L). \tag{11}$$

Using Equations (9) and (10) with Equation (11),

$$E_b(t) = e^{j(\omega_{th}t-\beta_o L)}e^{[-jF_2\frac{d^2}{dt^2}+F_3\frac{d^3}{dt^3}+\cdots]}E_L(t-\tau L). \tag{12}$$

Using Equations (3) and (12) and taking the exponential expansion

$$E_b(t) = e^{j(\omega_{th}t-\beta_o L)}\left[1 - jF_2\frac{d^2}{dt^2} + F_3\frac{d^3}{dt^3}\right]\sqrt{P_{in}}e^{j\phi(t-\tau L)}, \tag{13}$$

the output power can be obtained using

$$P_{out}(t) = |E_b(t)|^2. \tag{14}$$

Substituting Equation (13) in Equation (14) gives the following:

$$P_{out} = \left[|e^{j(\omega_{th}t-\beta_o L)}|\left|\left[1 - jF_2\frac{d^2}{dt^2} + F_3\frac{d^3}{dt^3}\right]\sqrt{P_{in}}e^{j\phi(t-\tau L)}\right|\right]^2, \tag{15}$$

$$P_{out} = P_{in}\left[\left|e^{j\phi(t-\tau L)} - j\underbrace{F_2\frac{d^2}{dt^2}e^{j\phi(t-\tau L)}}_{A} + \underbrace{F_3\frac{d^3}{dt^3}e^{j\phi(t-\tau L)}}_{B}\right|\right]^2, \tag{16}$$

$$P_{out} = P_{in}[|e^{j\phi(t-\tau L)} - jA + B|]^2, \tag{17}$$

$$\mathrm{A} = F_2\frac{d^2}{dt^2}e^{j\phi(t-\tau L)} = F_2\frac{d}{dt}\left(e^{j\phi(t-\tau L)}\cdot j\frac{d\phi}{dt}\right), \tag{18}$$

$$\mathrm{A} = jF_2 e^{j\phi(t-\tau L)}\left(\frac{d^2\phi}{dt^2} + j\left(\frac{d\phi}{dt}\right)^2\right), \tag{19}$$

$$\mathrm{B} = F_3\frac{d^3}{dt^3}e^{j\phi(t-\tau L)} = jF_3\frac{d}{dt}\left[e^{j\phi(t-\tau L)}\left(\frac{d^2\phi}{dt^2} + j\left(\frac{d\phi}{dt}\right)^2\right)\right], \tag{20}$$

$$\mathrm{B} = F_3 e^{j\phi(t-\tau L)}\left[-3\left(\frac{d\phi}{dt}\right)\cdot\frac{d^2\phi}{dt^2} + j\left(\frac{d^3\phi}{dt^3} - \left(\frac{d\phi}{dt}\right)^3\right)\right]. \tag{21}$$

Substituting Equations (19) and (21) in Equation (17) gives

$$P_{out} = \Bigg[\Bigg|e^{j\phi(t-\tau L)} + F_2 e^{j\phi(t-\tau L)}\left(\frac{d^2\phi}{dt^2} + j\left(\frac{d\phi}{dt}\right)^2\right) + F_3 e^{j\phi(t-\tau L)}\left[-3\left(\frac{d\phi}{dt}\right)\cdot\frac{d^2\phi}{dt^2} + j\left(\frac{d^3\phi}{dt^3} - \left(\frac{d\phi}{dt}\right)^3\right)\right]\Bigg|\Bigg]^2, \tag{22}$$

$$P_{out} = P_{in}\Bigg[|e^{j\phi(t-\tau L)}|\Bigg|1 + F_2\left(\frac{d^2\phi}{dt^2} + j\left(\frac{d\phi}{dt}\right)^2\right) + F_3\left[-3\left(\frac{d\phi}{dt}\right)\cdot\frac{d^2\phi}{dt^2} + j\left(\frac{d^3\phi}{dt^3} - \left(\frac{d\phi}{dt}\right)^3\right)\right]\Bigg|\Bigg]^2, \tag{23}$$

$$P_{out} = P_{in}\Bigg[\Bigg|\left(1 + F_2\frac{d^2\phi}{dt^2} - 3F_3\left(\frac{d\phi}{dt}\right)\cdot\frac{d^2\phi}{dt^2}\right) + j\left[F_2\left(\frac{d\phi}{dt}\right)^2 + F_3\left(\frac{d^3\phi}{dt^3} - \left(\frac{d\phi}{dt}\right)^3\right)\right]\Bigg|\Bigg]^2. \tag{24}$$

Now we evaluate the modulus of the above function:

$$P_{out} = P_{in}\left[\sqrt{\left[1 + F_2\frac{d^2\phi}{dt^2} - 3F_3\left(\frac{d\phi}{dt}\right)\cdot\frac{d^2\phi}{dt^2}\right]^2 + \left[F_2\left(\frac{d\phi}{dt}\right)^2 + F_3\left(\frac{d^3\phi}{dt^3} - \left(\frac{d\phi}{dt}\right)^3\right)\right]^2}\right]^2, \tag{25}$$

$$P_{out} = P_{in}\left[\sqrt{\begin{aligned}&1 + \left(F_2\frac{d^2\phi}{dt^2}\right)^2 + \left(3F_3\left(\frac{d\phi}{dt}\right)\cdot\frac{d^2\phi}{dt^2}\right)^2 + 2F_2\frac{d^2\phi}{dt^2}\\ &- 6F_3\left(\frac{d\phi}{dt}\right)\cdot\frac{d^2\phi}{dt^2} - 6F_2F_3\left(\frac{d^2\phi}{dt^2}\right)^3 + F_2^2\left(\frac{d\phi}{dt}\right)^4\\ &+ \left(F_3\frac{d^3\phi}{dt^3}\right)^2 + \left(F_3\left(\frac{d\phi}{dt}\right)^3\right)^2 + 2F_2F_3\left(\frac{d\phi}{dt}\right)^2\frac{d^3\phi}{dt^3}\\ &- 2F_2F_3\left(\frac{d\phi}{dt}\right)^5 - 2F_3^2\frac{d^3\phi}{dt^3}\left(\frac{d\phi}{dt}\right)^3\end{aligned}}\right]^2. \tag{26}$$

In Equation (26), neglecting the squared, higher terms and evaluating, we get

$$P_{out} = P_{in}\left(1 + 2F_2\frac{d^2\phi}{dt^2} - 6F_3\left(\frac{d\phi}{dt}\right)\cdot\frac{d^2\phi}{dt^2}\right). \tag{27}$$

Even though the input power P_{in} is constant, the phase noise $\phi(t)$ will be converted to intensity noise at the output because of the dispersion, as expressed by F_2 and F_3. If the two-sided spectral power density for the frequency noise $d\phi/dt$ is given by

$$\frac{d\phi}{dt} = W_\phi(\omega_m), \tag{28}$$

then the spectral power density for $d^2\phi/dt^2$ is given as

$$\frac{d^2\phi}{dt^2} = \omega_m^2 W_\phi(\omega_m). \tag{29}$$

So the RIN of P_{out} per noise bandwidth can be written as

$$\frac{RIN}{\Delta f} = 2\frac{\left[2F_2\frac{d^2\phi}{dt^2} - 6F_3\frac{d^2\phi}{dt^2}\frac{d\phi}{dt}\right]^2}{(\omega_m)^2 W_\phi(\omega_m)}, \tag{30}$$

$$\frac{RIN}{\Delta f} = \frac{8\left[\left(F_2\frac{d^2\phi}{dt^2}\right)^2 + \left(3F_3\frac{d^2\phi}{dt^2}\frac{d\phi}{dt}\right)^2 - 6F_2F_3\left(\frac{d^2\phi}{dt^2}\right)^2\frac{d\phi}{dt}\right]}{(\omega_m)^2 W_\phi(\omega_m)}, \tag{31}$$

$$\frac{RIN}{\Delta f} = \frac{\begin{array}{c}8[F_2^2((\omega_m)^2 W_\phi(\omega_m))^2 + 9F_3^2((\omega_m)^2 W_\phi(\omega_m))^2(W_\phi(\omega_m))^2 \\ -6F_2F_3((\omega_m)^2 W_\phi(\omega_m))^2 W_\phi(\omega_m)]\end{array}}{(\omega_m)^2 W_\phi(\omega_m)}, \tag{32}$$

$$\frac{RIN}{\Delta f} = 8((\omega_m)^2 W_\phi(\omega_m))[F_2^2 + 9F_3^2(W_\phi(\omega_m))^2 - 6F_2F_3W_\phi(\omega_m)]. \tag{33}$$

The RIN at the output thus represents the frequency noise of the laser, multiplied by (noise frequency)$^{2\nu}$. We can assume that a white frequency noise spectrum yields a Lorentzian line shape with a spectral width [6]:

$$\Delta\nu = \frac{W_\phi}{2\pi}. \tag{34}$$

Further we have $\omega_m = 2\pi f$. By putting the above values in Equation (18), we have

$$\frac{RIN}{\Delta f} = 8((2\pi)^3 f^2 \Delta\nu)[F_2^2 + 9F_3^2(2\pi\Delta\nu)^2 - 6F_2F_3 2\pi\Delta\nu]. \tag{35}$$

Equation (35) shows the RIN variation depending upon the second- and third-order dispersion terms. As we see from this equation, the term containing only second-order dispersion (F_2) is the same as shown by Petermann [5], but we must have two additional terms, one containing the third-order dispersion term only (F_3) and other containing both second-order dispersion (F_2) and third-order dispersion (F_3). Moreover, the laser linewidth factor has also been included in the modified expression.

Results and Discussions

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

$$F_2 = 12.75 \times 10^{-24}\ \mathrm{L/km}, \tag{36}$$

$$F_3 = 2.955 \times 10^{-38}\ \mathrm{L/km}. \tag{37}$$

Now using Equation (35) we plot RIN with frequency as shown in Figure 1. For constant linewidth $\Delta\nu = 100$ MHz, we observe that as the noise frequencies are increased, the RIN factor increases. The results agree with the results reported by Peterman [5]. We also observe that the plot with the second-order dispersion term coincides with the plot with second- and third-order dispersion terms together.

This reflects that the third-order dispersion term has no impact on RIN even at high noise frequencies. The same results were given by Cartexo and Morgado [8] and Kaler et al. [3]. But with second-order dispersion compensation (i.e., $F_2 = 0$) by means of available compensating devices, it is observed that RIN values can be dramatically reduced, thereby improving overall system performance. We observe that the value of RIN can be brought to −700 dB/Hz from −240 dB/Hz at 100 GHz noise frequency with second-order dispersion compensation. Indeed, such a reduction in RIN will be very fruitful in designing long-haul ultra-high-bit-rate systems. This compensation effect was not shown by any previous authors.

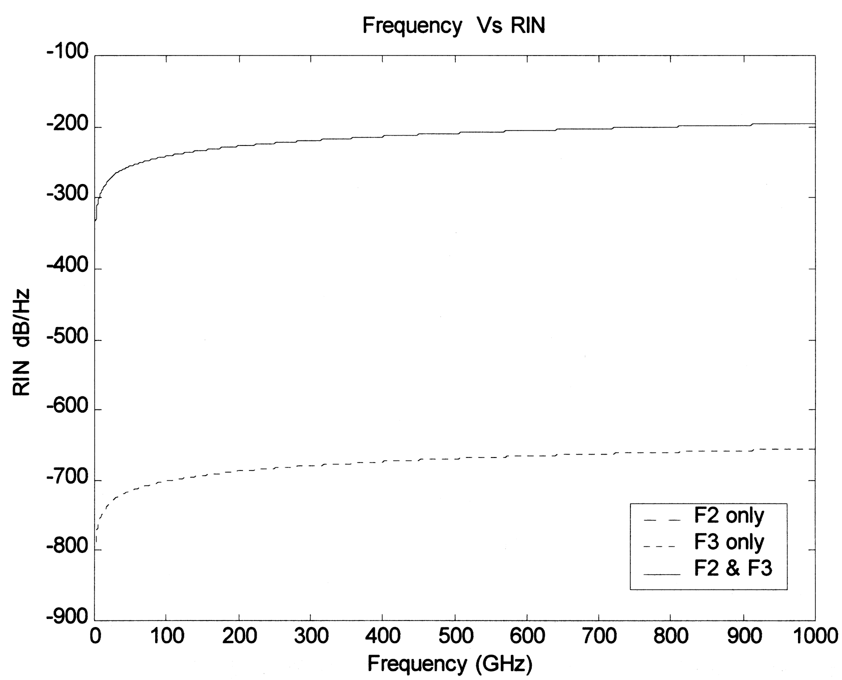

Figure 1. RIN plotted against frequency with second-, third-, and second- and third-(together) order dispersion parameters according to Equation (35).

Further, we observe the influence of another important parameter, laser linewidth, on RIN. The approach today is toward narrow linewidths. 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 ordinary lasers 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.

We now plot RIN against noise frequencies for different linewidths ($\Delta\nu = 25$, 50, and 100 MHz) as shown in Figure 2. It is observed that for lower linewidths the value of RIN gets reduced. If the linewidth is decreased from 100 to 25 MHz, the 14 dB reduction is noticed at 100 GHz frequency. The graph with second-order dispersion compensation ($F_2 = 0$) showing the same effect is shown in Figure 3. Again it is observed that RIN gets reduced by 458 dB at 100 GHz frequency at 100 MHz linewidth.

In order to study the influence of fiber length on RIN including second- and third-order dispersion terms, we plot for different lengths $L = 10$, 25, 50, and 80 km as shown in Figure 4. We observe that for different fiber lengths, the RIN value changes drastically. The RIN value increases with length of the fiber, which is quite obvious. Also the RIN values are higher at the higher frequency for the same fiber length. The results agree with the results given by Petermann [5], who plotted for length up to 30 km with second-order dispersion only. The plot for the same fiber lengths with F_3 only is shown in Figure 5, which indicates the dispersion compensation. Again, it is clear from the figure that the value of RIN has decreased drastically for different fiber lengths. For 80 km length, the improvement of 450 dB/km is found with second-order compensation.

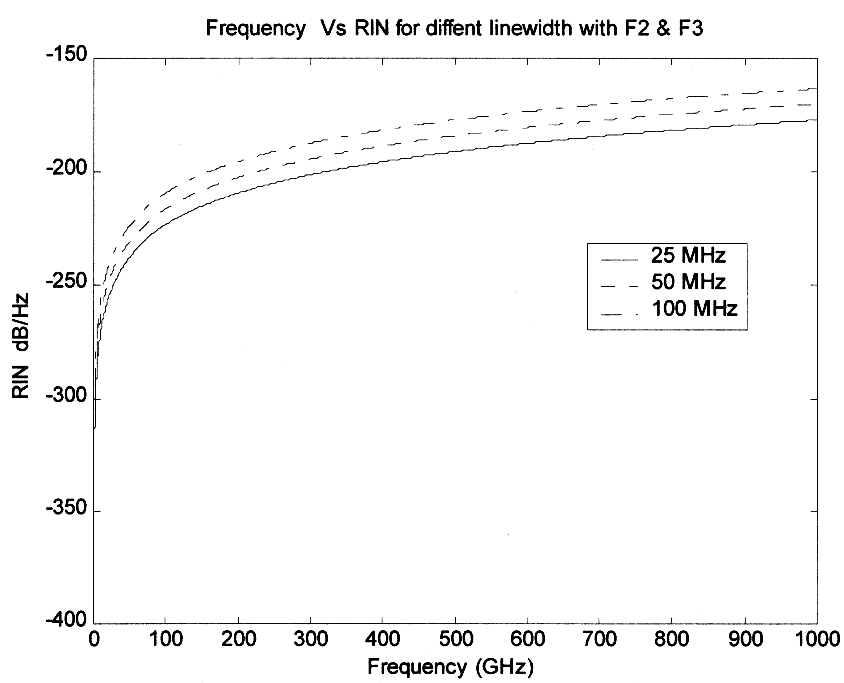

Figure 2. RIN plotted against frequency with second- and third-order dispersion parameters for different linewidth frequencies, $\Delta\nu = 25$, 50, 100 MHz.

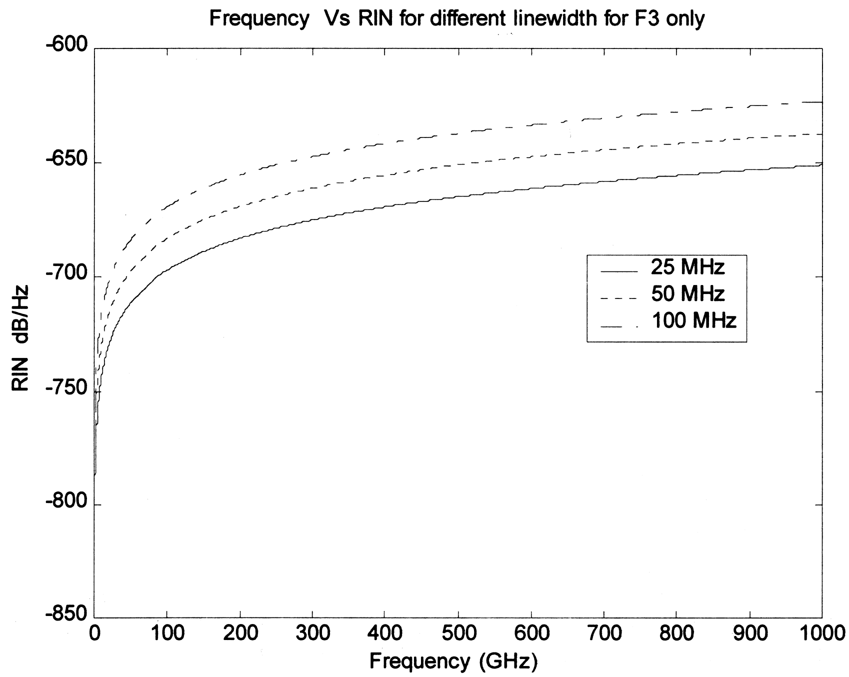

Figure 3. RIN plotted against frequency with third-order dispersion parameters for different linewidth frequencies, $\Delta\nu = 25$, 50, 100 MHz.

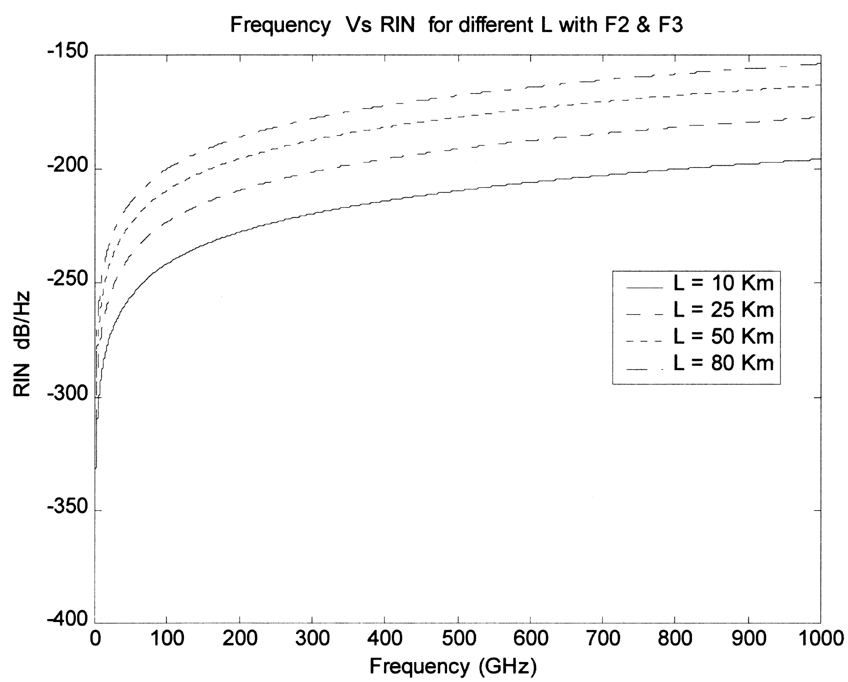

Figure 4. RIN plotted against frequency with second- and third-order dispersion parameters for different lengths, $L = 10$, 25, 50, 80 km.

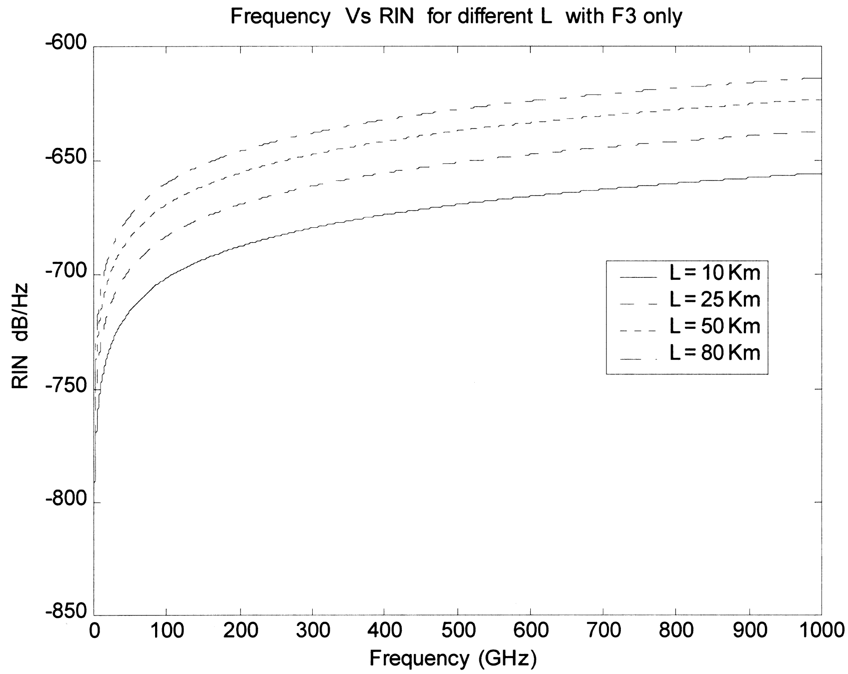

Figure 5. RIN plotted against frequency with third-order dispersion parameters for different lengths, $L = 10$, 25, 50, 80 km.

Conclusions

The modified expression for RIN has been derived including third-order dispersion for dispersive optical communication systems. It has been shown that the third-order dispersion term has no impact on RIN even at high noise frequencies, but with second-order dispersion compensation the RIN values can be dramatically reduced, thereby improving overall system performance. It has been shown that with second-order dispersion compensation there is 460 dB improvement in the value of RIN at 100 GHz noise frequency. Further, the impact of fiber length and laser linewidth has been investigated for RIN. It has been shown that as the fiber length increases, the value of RIN increases, but the improvement over RIN decreases with second-order dispersion compensation. Also, with decrease in the value of linewidth, the RIN value is reduced.

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Biographies

Harish Kumar was born in Barnala, Punjab, India on 16 October 1976. He obtained his Bachelor's degree in electronics engineering from Punjab Technical University, Jalandhar, Punjab, India, and M. Tech. degree from Panjab University, Chandigarh, India in 1998 and 2002, respectively. He has worked as a lecturer in the Electronics and Communication Engineering Department, SLIET, Longowal, Punjab, India, since 2000. His present interests are fiber dispersion and nonlinearities. He has over eight research papers in international and national journals and conferences. He is a life associate member of the Institution of Engineers (India).

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