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Validity of third-order dispersion term for single-mode fiber near zero dispersion wavelength

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Abstract

The paper presents the validity of third order dispersion term for dispersive optical communication systems operating near zero dispersion wavelength for single-mode fiber. We show that the second-order dispersion term has no effect on intensity and frequency response even at large modulating frequencies and large propagation distances as reported by other authors but on carrying the analysis further we show that the third-order dispersion term certainly has some minute impact on the frequency response and significant impact on the relative intensity noise (RIN) response for long distance links at high-modulating frequencies.

Keywords: Broadband communications; Dispersion; Laser noise; Relative intensity noise; Higher-order dispersion; Frequency response

1. Introduction

The 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 [1,2] rather by the fiber loss [3] because it introduces signal distortion and noise [4,5]. 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 [6–8]. There is not only the impact of first-order dispersion term but also the higher-order dispersion terms have significant impact on the performance of broadband optical communication systems [9,10].

Wang et al. [11] developed a new approach to investigate the influence of the dispersion on optical fiber communication systems using small-signal analysis near zero dispersion wavelength. The conversion

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between phase and intensity modulation or noise caused by chromatic dispersion had been analyzed for laser diodes. 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 with first-order dispersion.

A theory describing the propagation of signal and noise through a lossless linear dispersive single-mode fiber with first- and second-order dispersion was presented by Crognale [12] near zero dispersion wavelength. Recalling the small-signal approach reported in [11], a simple and exhaustive treatment was developed to study the small-signal and noise transmission characteristics in the frequency domain of a high performance laser diode together with a linear dispersive fiber. The impact of second-order dispersion term on the modulation and noise properties of an ultrafast laser diode was obtained to study the total frequency response and the relative intensity noise (RIN) at output of the linear single-mode fiber but the impact of third and higher-order dispersion terms was neglected. It was shown that the second-order dispersion term had significant impact for long distance links at high modulating frequencies.

Cartaxo et al. [13] further carried out rigorous small-signal analysis using theoretical and numerical simulations for linear dispersive optical communication systems operating near zero wavelength. The theory contradicted the Crognale theory and indicated that the approximation assumed in [12] was not valid and the second-order dispersion term had no impact on frequency and RIN response for long distance links at high modulating frequencies. However, the analysis was again carried up to second-order dispersion term only.

In this paper, we have extended the work reported in [11–13] by presenting theoretical analysis for analyzing the influence up to third-order dispersion term on dispersive optical communication system. We follow the same method as reported in [12] but the approximation has been overcome to obtain more accurate small-signal relation allowing conversion between intensity and phase modulation or noise in a dispersive fiber including third-order dispersion terms. We show that the third-order dispersion term certainly has some impact on the frequency and RIN response for long distance links at high modulating frequencies.

2. Analysis

Let the electric field at the input of fiber from a single-mode laser diode [14]

$$E(t) = E_{\text{in}}(t)\mathrm{e}^{\mathrm{j}\omega_0 t}, \tag{1}$$

with the slowly varying complex amplitude $E_{\text{in}}(t)$ and the mean optical frequency ω_o which is given by [11].

$$E_{\text{in}}(t) = \sqrt{S_{\text{in}}(t)}\mathrm{e}^{\mathrm{j}\phi_{\text{in}}(t)}, \tag{2}$$

where $S_{\text{in}}(t)$ and $\phi_{\text{in}}(t)$ are, respectively, the input photon intensity and input phase. As in [15], the propagation of the signal through an optical fiber can be described by propagation term $\mathrm{e}^{-\mathrm{j}\beta L}$ with length L of the transmission fiber and the propagation constant β by the relation

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

The losses are neglected here as the signal distortion or noise is induced by chromatic dispersion rather than fiber loss as reported in [7,12,13]. The propagation constant β in terms of Taylor series can be expanded around $\omega = \omega_o$ as [15–17]

$$\beta = \beta_o + (\omega - \omega_o)\tau - (\omega - \omega_o)^2 F_2 + (\omega - \omega_o)^3 F_3 - (\omega - \omega_o)^4 F_4 + \frac{1}{120}(\omega - \omega_o)^5 F_5 \cdots, \tag{4}$$

where $d\beta/d\omega = \tau$ is the group delay for unit length and F_2, F_3, F_4 and F_5 are, respectively, first-, second-, third- and fourth-order dispersion terms. As reported in [15–17], we neglect the absolute phase ($\phi_o = \beta_o L$) and group delay ($d\beta/d\omega = \tau$ and corresponds to F_1 term) because both terms produce only phase delay of the carrier signal and have no influence on the distortion of the signal

$$E_{out}(j\omega) = E_{in}(j\omega)e^{jF_2(\omega-\omega_o)^2 - jF_3(\omega-\omega_o)^3 + jF_4(\omega-\omega_o)^4 - jF_5(\omega-\omega_o)^5\cdots}. \quad (5)$$

In time domain, since ($j\omega = \frac{\partial}{\partial t}$), ($(j\omega)^2 = -\omega^2 = \frac{\partial^2}{\partial t^2}$) and ($(j\omega)^3 = -j\omega^3 = \frac{\partial^3}{\partial t^3}$) etc.,

$$E_{out}(t) = e^{j\omega_o t}e^{\left(-jF_2\frac{\partial^2}{\partial t^2} + F_3\frac{\partial^3}{\partial t^3} - jF_4\frac{\partial^4}{\partial t^4} + F_5\frac{\partial^5}{\partial t^5}\cdots\right)}\sqrt{S_{in}(t)}e^{j\phi_{in}(t)}. \quad (6)$$

Let

$$E_{out}(t) = E_{in}(t) + \Delta E(t), \quad (7)$$

where

$$|\Delta E(t)| \ll |E_{in}(t)|. \quad (8)$$

From Eqs. (6) and (7)

$$\Delta E(t) = \left(e^{\left(-jF_2\frac{\partial^2}{\partial t^2} + F_3\frac{\partial^3}{\partial t^3} - jF_4\frac{\partial^4}{\partial t^4} + F_5\frac{\partial^5}{\partial t^5}\cdots\right)} - 1\right)\sqrt{S_{in}(t)}e^{j\phi_{in}(t)}. \quad (9)$$

From (7) and with the help of approximation (8), we have

$$S_{out}(t) = |E_{in}(t) + \Delta E(t)|^2 \approx |E_{in}(t)|^2 + r\mathscr{R}[E^*_{in}(t)\Delta E(t)]. \quad (10)$$

Substituting Eqs. (2) and (9) in Eq. (10)

$$S_{out} = S_{in}(t) + 2\mathscr{R}\left[\sqrt{S_{in}(t)}e^{-j\phi_{in}(t)}\left(e^{\left(-jF_2\frac{\partial^2}{\partial t^2} + F_3\frac{\partial^3}{\partial t^3} - jF_4\frac{\partial^4}{\partial t^4} + F_5\frac{\partial^5}{\partial t^5}\cdots\right)} - 1\right)\sqrt{S_{in}(t)}e^{j\phi_{in}(t)}\right], \quad (11)$$

$$\therefore \phi_{out}(t) = \phi_{in}(t) + \mathscr{J}\left[\frac{\Delta E(t)}{E_{in}(t)}\right], \quad (12)$$

$$\phi_{out}(t) = \phi_{in}(t) + \mathscr{J}\left[\frac{\left(e^{\left(-jF_2\frac{\partial^2}{\partial t^2} + F_3\frac{\partial^3}{\partial t^3} - jF_4\frac{\partial^4}{\partial t^4} + F_5\frac{\partial^5}{\partial t^5}\cdots\right)} - 1\right)\sqrt{S_{in}(t)}e^{j\phi_{in}(t)}}{\sqrt{S_{in}(t)}e^{j\phi_{in}(t)}}\right]. \quad (13)$$

Eqs. (11) and (13) derived above are the general equations describing the intensity and phase of an optical field after propagating through a dispersive optical fiber.

The small-signal analysis implies that fluctuations $\Delta S_{in}(t)$ (including fluctuations with frequency modulation or noise $\phi = d\phi/dt$) are smaller than the average intensity $\langle S\rangle$ in the total signal $S_{in}(t)$

$$S_{in}(t) = \langle S\rangle + \Delta S_{in}(t) \quad (14)$$

with $\langle S\rangle \gg \Delta S_{in}(t)$.

As reported in [11,12] in the small-signal approach, the field amplitude $\sqrt{S_{in}(t)}$ can be linearized as

$$\sqrt{S_{in}(t)} \approx \sqrt{\langle S\rangle}\left(1 + \frac{\Delta S_{in}(t)}{2\langle S\rangle}\right). \quad (15)$$

After neglecting the product of small-signal [11,12,20], we can introduce following approximations:

$$\frac{\partial^n}{\partial t^n}\left(\sqrt{S_{in}(t)}e^{j\phi_{in}(t)}\right) \approx \sqrt{S_{in}(t)}e^{j\phi_{in}(t)}\frac{\partial^n}{\partial t^n}\sqrt{\langle S\rangle}\left(j\phi_{in}(t) + \frac{\Delta S_{in}(t)}{2\langle S\rangle}\right). \quad (16)$$

Inserting (16) into (11) and (13), we obtain

$$S_{\mathrm{out}}(t) = S_{\mathrm{in}}(t) + 2\mathscr{R}\left[\langle S\rangle\left(\mathrm{e}^{\left(-\mathrm{j}F_2\frac{\partial^2}{\partial t^2}+F_3\frac{\partial^3}{\partial t^3}-\mathrm{j}F_4\frac{\partial^4}{\partial t^4}+F_5\frac{\partial^5}{\partial t^5}\cdots\right)}\right)\left(\frac{\Delta S_{\mathrm{in}}(t)}{2\langle S\rangle}+\mathrm{j}\phi_{\mathrm{in}}(t)\right)\right], \tag{17}$$

with $S_{\mathrm{in}}(t) \approx \langle S\rangle$ as (14) with $\langle S\rangle \gg \Delta S_{\mathrm{in}}(t)$ and similarly as

$$\phi_{\mathrm{out}}(t) = \mathscr{I}\left[\left(\mathrm{e}^{\left(-\mathrm{j}F_2\frac{\partial^2}{\partial t^2}+F_3\frac{\partial^3}{\partial t^3}-\mathrm{j}F_4\frac{\partial^4}{\partial t^4}+F_5\frac{\partial^5}{\partial t^5}\cdots\right)}\right)\left(\frac{\Delta S_{\mathrm{in}}(t)}{2\langle S\rangle}+\mathrm{j}\phi_{\mathrm{in}}(t)\right)\right]. \tag{18}$$

The exponential operator can be written as [12]

We have

$$\mathrm{e}^{\left(-\mathrm{j}F_2\frac{\partial^2}{\partial t^2}+F_3\frac{\partial^3}{\partial t^3}-\mathrm{j}F_4\frac{\partial^4}{\partial t^4}+F_5\frac{\partial^5}{\partial t^5}\cdots\right)} \approx \left[\cos\left(F_2\frac{\partial^2}{\partial t^2}+F_4\frac{\partial^4}{\partial t^4}\right) - \mathrm{j}\sin\left(F_2\frac{\partial^2}{\partial t^2}+F_4\frac{\partial^4}{\partial t^4}\right)\right]\left(\mathrm{e}^{F_3\frac{\partial^3}{\partial t^3}+F_5\frac{\partial^5}{\partial t^5}}\right). \tag{19}$$

In this way the relations for intensity and phase derived at the fiber output are:

$$\Delta S_{\mathrm{out}}(t) = \left[\cos\left(F_2\frac{\partial^2}{\partial t^2}+F_4\frac{\partial^4}{\partial t^4}\right) + 2\langle S\rangle\sin\left(F_2\frac{\partial^2}{\partial t^2}+F_4\frac{\partial^4}{\partial t^4}\right)\right]\left[\left(\mathrm{e}^{F_3\frac{\partial^3}{\partial t^3}+F_5\frac{\partial^5}{\partial t^5}}\right)\left(\frac{\Delta S_{\mathrm{in}}(t)}{2\langle S\rangle}+\mathrm{j}\phi_{\mathrm{in}}(t)\right)\right], \tag{20}$$

$$\phi_{\mathrm{out}}(t) = \left[\cos\left(F_2\frac{\partial^2}{\partial t^2}+F_4\frac{\partial^4}{\partial t^4}\right) - 2\sin\left(F_2\frac{\partial^2}{\partial t^2}+F_4\frac{\partial^4}{\partial t^4}\right)\right]\left[\left(\mathrm{e}^{F_3\frac{\partial^3}{\partial t^3}+F_5\frac{\partial^5}{\partial t^5}}\right)\left(\frac{\Delta S_{\mathrm{in}}(t)}{2\langle S\rangle}+\mathrm{j}\phi_{\mathrm{in}}(t)\right)\right], \tag{21}$$

with the output modulation or noise given by

$$\Delta S_{\mathrm{out}}(t) = S_{\mathrm{out}}(t) - \langle S\rangle \tag{22}$$

and dots denote the time derivatives. Recalling the relation between frequency and phases [11,12], we take practical systems and consider frequency modulation or noise $\phi = \mathrm{d}\phi/\mathrm{d}t$ rather than phase modulation. The results may be expressed with modified conversion matrix that describes the relation between intensity and frequency including the second-, third-, and fourth-order dispersion terms as shown in expression (20) and (21). Also the new results can be derived by including or excluding the respective higher-order dispersion terms.

$$\begin{pmatrix}\Delta S_{\mathrm{out}}(\omega)\\ \dot{\phi}_{\mathrm{out}}(\omega)\end{pmatrix} = \begin{pmatrix} \cos\left(F_2\omega^2+F_4\omega^4+\cdots F_{2n}\omega^{2n}\right)\left(\mathrm{e}^{-\mathrm{j}F_3\omega^3-\cdots\mathrm{j}F_{2n+1}\omega^{2n+1}}\right) & \cdots\frac{2\mathrm{j}\langle S\rangle}{\omega}\sin\left(F_2\omega^2+F_4\omega^4+\cdots F_{2n}\omega^{2n}\right)\left(\mathrm{e}^{\mathrm{j}F_3\omega^3-\cdots\mathrm{j}F_{2n+1}\omega^{2n+1}}\right) \\ \frac{\mathrm{j}\omega\sin\left(F_2\omega^2+F_4\omega^4+\cdots F_{2n}\omega^{2n}\right)}{2\langle S\rangle}\left(\mathrm{e}^{-\mathrm{j}F_3\omega^3-\cdots\mathrm{j}F_{2n+1}\omega^{2n+1}}\right)\cdots & \left(\mathrm{e}^{-\mathrm{j}F_3\omega^3-\cdots\mathrm{j}F_{2n+1}\omega^{2n+1}}\right)\cdots\cos\left(F_2\omega^2+F_4\omega^4+\cdots F_{2n}\omega^{2n}\right)\end{pmatrix} \times \begin{pmatrix}\Delta S_{\mathrm{in}}(\omega)\\ \phi_{\mathrm{in}}(\omega)\end{pmatrix}. \tag{23}$$

If we consider a modulation of the injection current around the mean value $\langle I\rangle$, the small-signal response of the laser source may be obtained with small-signal modulation current ΔI, so that $|\Delta I| \ll \langle I\rangle$, yielding in frequency domain [12]

$$\Delta S_{\mathrm{in}}(\omega) = \left(\frac{\tau_{\mathrm{ph}}}{e}\right)H(\omega)\Delta I(\omega), \tag{24}$$

where τ_{ph} is the photon lifetime, e is the elementary charge and the small-signal modulation transfer function [12]

$$H(\omega) = \frac{\omega_r^2}{(j\omega)^2 + j\omega\Gamma + \omega_r^2}. \tag{25}$$

Here, the Γ is the damping rate. The relation between frequency modulation and intensity modulation (chirp) may be described by [14,21]

$$\phi_{\text{in}}(\omega) = \frac{\alpha}{2}(j\omega + \omega_g)\frac{\Delta S_{\text{in}}(\omega)}{\langle S \rangle}, \tag{26}$$

where, α is the linewidth enhancement factor, and ω_g is the device-specific characteristic frequency. If the chirp characteristics are mainly due to nonlinear gain, we have $\omega_g \approx \Gamma$. The intensity modulation at the fiber output can be obtained by inserting above Eqs. (24)–(26) into (23)

$$\left|\frac{\Delta S_{\text{out}}}{\Delta I(\omega)}\right| = \left(\frac{\tau_{\text{ph}}}{e}\right)\left\{\left|e^{-jF_3\omega^3}\right|\right\}\left[\cos(F_2\omega^2 + F_4\omega^4) + j\alpha\sin(F_2\omega^2 + F_4\omega^4)\frac{j\omega + \omega_g}{\omega}\right]H(\omega). \tag{27}$$

Expression (27) gives intensity modulation at output of a dispersive fiber including the effects of first-, second-, third- and fourth-order dispersion terms.

Similarly, we can derive and analyze the impact of other independent and combined higher-order dispersion terms for semiconductor laser noise with spontaneous emission rate and average photon density. Assuming the laser noise induced predominantly by the spontaneous emission noise, the Langevin noise sources for intensity and phase are given by [11,14]

$$\langle |F_s(\omega)|^2 \rangle = 2R\langle S \rangle, \tag{28}$$

$$\langle |F_\phi(\omega)|^2 \rangle = \frac{R}{2\langle S \rangle}, \tag{29}$$

where R and $\langle S \rangle$ are spontaneous emission rate and average photon density, respectively, of the semiconductor laser diode with

$$\langle \Delta F_s\omega(\Delta)F_\phi^*(\omega) \rangle = 0. \tag{30}$$

As reported in [11], we have

$$\Delta S(\omega) = \left(\frac{\frac{1}{\tau_e'} + j\omega}{\omega_R^2}\right)H(\omega)\Delta F_s(\omega), \tag{31}$$

$$\phi(\omega) = \frac{-\alpha\omega_R^2}{2\left(j\omega + \frac{1}{\tau_e'}\right)}\frac{\Delta S\omega}{\langle S \rangle} + \Delta F_\phi(\omega), \tag{32}$$

with [11] describing the features of laser diode.

$$\frac{1}{\tau_e'} = \frac{1}{\tau_e} + \omega_R^2\tau_{\text{ph}}. \tag{33}$$

It is useful to introduce a "relative intensity noise" (RIN) relating the intensity fluctuations $\Delta S(\omega)$, referred to a noise bandwidth Δf, to mean intensity $\langle S \rangle$. By definition [12],

$$\frac{\text{RIN}}{\Delta f} = \frac{2\langle |\Delta S(\omega)|^2 \rangle}{\langle S \rangle^2}. \tag{34}$$

From (33) and (34), the intrinsic RIN of semiconductor laser may be written as

$$\frac{\text{RIN}}{\Delta f} = \frac{4R}{\langle S \rangle}\left(\frac{\frac{1}{\tau_e'^2} + \omega^2}{\omega_R^4}\right)|H(\omega)|^2. \tag{35}$$

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 due to higher-order dispersion terms.

The FM–AM noise conversion with the intensity and phase noise of the laser source has been investigated in [18–21]. Recalling the results obtained in [11,12], and the modified conversion matrix (23), one finally obtains the RIN at the fiber output due to higher-order dispersion terms by inserting Eqs. (31), (32) in (23) and recalling (35)

$$\frac{\mathrm{RIN}}{\Delta f} = \frac{4R}{\langle S\rangle}\left\{|\mathrm{e}^{\mathrm{j}F_3\omega^3}|\right\}\left\{\frac{1+\omega^2\tau_e'^2}{\omega_R^4\tau_e'^2}|H(\omega)|^2\cos^2(\omega^2F_2+\omega^4F_4) + (\alpha^2|H(\omega)|^2+1)\frac{\sin^2(\omega^2F_2+\omega^4F_4)}{\omega^2} - \frac{\alpha\sin^2(2\omega^2F_2+2\omega^4F_4)}{\omega_R^2}|H(\omega)|^2\right\}. \tag{36}$$

Eqs. (27) and (36) are the accurate equations and will be used to study the impact of higher-order dispersion terms.

3. Results and discussions

Referring to ITU:T Recommendations G.653 [22] up to fourth-order dispersion term, we assume that for DS fiber near 1550 nm

$$\frac{\mathrm{d}\tau}{\mathrm{d}\lambda} = (\lambda-\lambda_o)S_o \tag{37}$$

in which $S_o = (\mathrm{d}^2\tau/\mathrm{d}\lambda^2)$ is zero dispersion slope and λ_o is zero dispersion wavelength. Imposing $\lambda_o = 1550$ nm and $S_o = 0.085$ ps/nm^2/km, we have $(\mathrm{d}\tau/\mathrm{d}\lambda) = 5\times10^{-3}$ ps/nm/km, $(\mathrm{d}^2\tau/\mathrm{d}\omega^2) = 0.138$ ps^3/km and $(\mathrm{d}^3\tau/\mathrm{d}\omega^3) = 0.000618$ ps^4/km. The other semiconductor laser parameters are relaxation resonance frequency $f_R = 20.25$ GHz, damping rate $\Gamma = 63.29$ GHz, spontaneous emission rate $R = 2.54\times10^{12}$ s^{-1}, average photon density $\langle S\rangle = 4.5\times10^5$, photon life time $\tau_{ph} = 118\times10^{-12}$s $\tau_e = 0.17\times10^{-9}$ s, linewidth enhancement factor $\alpha = 5$ and maximum intrinsic modulation width $f_{max} = 63.47$ GHz.

In order to see the validity of the third-order dispersion term, we plot the frequency response by taking Eq. (27) for various different combination cases of first-, second- and third-order dispersion terms. Fig. 1 indicates the comparison of these three cases at 10,000 km distance. It is clear from the figure that second-order dispersion term has no impact on frequency response even at large propagation distances at long distance links as both the plots (with F2 only and with combined F2 and F3) coincide. But there is some impact of F4 as minute deviations are observed. The drop in frequency response for F2 only and with F2 and F3 together is at the same frequency whereas this drop for F2, F3 and F4 together is at slightly low frequency. Thus, we conclude that the second-order dispersion effects are none but there are certainly some minute third-order dispersion effects at high-modulating frequencies and large propagation distances.

In order to see the validity of third-order dispersion term for RIN effect, we now investigate the RIN response according to Eq. (36). For same set of parameters, we plot RIN response with modulation frequencies for various combination cases of first-, second- and third-order dispersion terms as shown in Fig. 2. Fig. 2 indicates the comparison of these three cases at $L = 10{,}000$ km. It is clear from the figure that second-order dispersion term has no impact on frequency response even at large propagation distances at long distance links as again both the plots (with F2 and combined F2 and F3) coincide. But there is some impact of F4 as significant deviations are observed in comparison with the combined effect of F2 and F3. It is also seen that the drop in frequency response for F2 only and with F2 and F3 together is at the same frequency whereas this drop for F2, F3 and F4 together is at slightly high frequency. Thus, we conclude

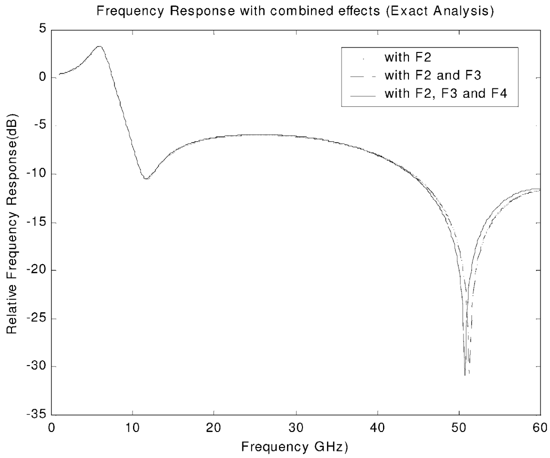

Fig. 1. Small-signal frequency response for different combinations of F2, F3 and F4 according to Eq. (27) for $L = 10{,}000$ km with $S_o = 0.085$ ps/nm^2/km, $(d\tau/d\lambda) = 5 \times 10^{-3}$ ps/nm/km, $(d^2\tau/d\omega^2) = 0.138$ ps^3/km and $(d^3\tau/d\omega^3) = 0.000618$ ps^4/km.

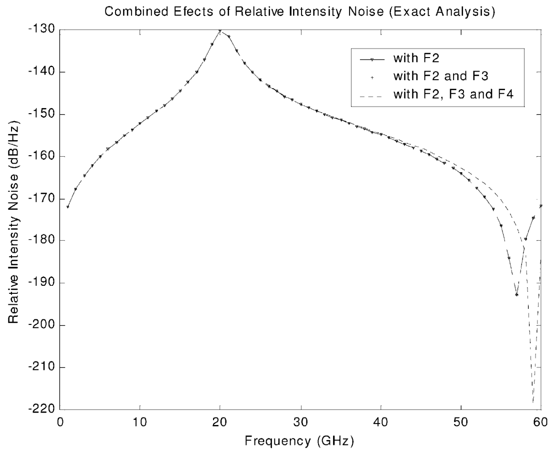

Fig. 2. Small-signal relative intensity noise (RIN) response for different combinations of F2, F3 and F4 according to Eq. (36) for $L = 10{,}000$ km with $S_o = 0.085$ ps/nm^2/km, $(d\tau/d\lambda) = 5 \times 10^{-3}$ ps/nm/km, $(d^2\tau/d\omega^2) = 0.138$ ps^3/km and $(d^3\tau/d\omega^3) = 0.000618$ ps^4/km.

that second-order dispersion effects are none but there are certainly some third-order dispersion effects at high-modulating frequencies and large propagation distances.

4. Conclusions

In this paper, we have developed the theory to investigate the influence of third-order dispersion terms on optical communication systems using small-signal analysis. The theory developed in this paper may be considered as extension of the results reported in [12,13], where the impact of third-order dispersion terms was neglected. We show that the third-order dispersion term certainly has some impact on the frequency response and significant impact on RIN response for long distance links at high-modulating frequencies.

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