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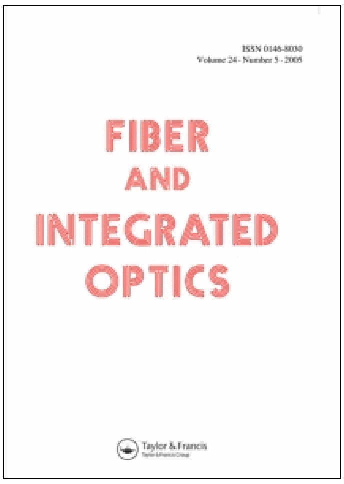

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Improved Analysis of Dispersion Compensation Using Differential Time Delay for High-Speed Long-Span Optical Link

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A dispersion-compensation technique using differential time delay has been analyzed for a high bit rate dispersive limited system using higher order dispersion terms. The technique is based on splitting the power spectrum into upper and lower parts, corresponding to the two modulation sidebands, and delaying one of these with respect to the other. RMS, phase deviation, dimension free chirp parameter, and figure of merit have been evaluated due to higher order dispersion terms for ideal and realistic optical communication systems. It has been shown that the transmission distance could be enhanced to fourfold, sixfold, and eightfold when the compensation has been performed using second-, third-, and fourth-order dispersion (2OD, 3OD, and 4OD) terms.

Keywords chirp parameter, compensating device, dispersion, figure of merit, phase deviation

An important limitation to the bit rate–distance product achievable in a fiber optic communication link arises because of the *group-velocity dispersion* (GVD) in the fiber [1, 2]. At higher bit rates, the dispersion-induced broadening of short pulses propagating in the fiber causes cross talk between the adjacent time slots, leading to errors when the communication distance increases beyond the dispersion length

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of the fiber. Several dispersion-compensation approaches have been followed to push the bit rate–distance product to higher values [3–12].

The prechirp technique is the most common way to deal with fiber dispersion [3–9]. The prechirp is normally obtained by the laser in both direct and external modulated experiments [3–5]. An attempt was made to examine the possibility of performing the prechirp of the transmitted signal by external modulator [6, 9]. There is another technique that is based on hetrodyne mixing and dispersion compensation at an internal microwave frequency on the receiver side [10]. A third known method uses an extra fiber with an inverse dispersion to compensate fiber dispersion [11]. The limitation of this method is the extra fiber loss and the cost of the dispersion-compensating fiber as mentioned in [13]. The fourth method is based on a spectral inversion at the midpoint of the transmission length, but this method offers a very low conversion rate [12]. The fifth method is based on dispersion compensation with phase-sensitive optical amplifies that can be implemented in both the positive and negative GVD regions [14]. The easiest and cheapest way to compensate for fiber dispersion is the prechirp technique. The disadvantage of this method is that it does not compensate for the dispersion thoroughly. On the other hand, the methods based on hetrodyne mixing, compensation fibers, and spectral inversion are expensive and complicated to implement in the communication system.

Recently, dispersion compensation using differential time delay was reported [13]. The scheme is primarily intended for high bit rate (> 10 G bit/s) time division multiplexed transmission, and in an ideal case the transmitting distance could be enhanced by a factor of four in a dispersive limited system. In this method the analysis and implementation is based on a second-order term of the propagation constant.

For fiber optic communication systems operating near the dispersion free wavelength of the fiber, an expansion to the higher order terms of the propagation constant is essential in order to design and develop an efficient high bit rate fiber optic communication systems. Therefore, it is important to compensate dispersion due to higher order terms of propagation constant [15]. In this article, we present an improved analysis for dispersion compensation using higher order terms of the propagation constant. Root mean square (RMS) phase deviation, figure of merit, and the chirp parameter for higher order dispersion terms have been evaluated and analyzed for ideal and realistic optical systems in detail.

Analysis

Here, it is assumed that the power level is very low to initiate any nonlinear effects in the optical fiber. Therefore, the transmission characteristics of the fiber are represented by the linear filter. In a linear system the most common way to express fiber dispersion is the Taylor expansion of the propagation constant (β) about optical carrier frequency (ω_c).

The propagation constant using the Taylor expansion may be expressed as

$$\beta = \beta_c + \frac{1}{v_g}(\omega - \omega_c) - \frac{\lambda^2 D}{4\pi c}(\omega - \omega_c)^2 + \cdots \tag{1}$$

where

$$\frac{1}{\nu_g} = \frac{d\beta}{d\omega} \tag{2}$$

$$D = \frac{d}{d\lambda}[1/\nu_g] = -\frac{2\pi C}{\lambda^2} \cdot \frac{d\beta^2}{d\omega^2} \tag{3}$$

After simplifying, the propagation constant is expressed as

$$\beta = \beta_c + D_1\,\Delta\omega + \tfrac{1}{2}D_2\,\Delta\omega^2 + \tfrac{1}{6}D_3\,\Delta\omega^3 + \tfrac{1}{24}D_4\,\Delta\omega^4 + \cdots \tag{4}$$

where $D_1 = d\beta/d\omega$, $D_2 = d\beta^2/d\omega^2, \ldots, D_n = d\beta^n/d\omega^n$; D_1, D_2, and D_n are first-, second-, and nth-order dispersion terms, respectively; $n = 1, 2, 3\ldots$; and $\Delta\omega = \omega - \omega_c$. At the receiver, the phase deviation might now be expressed as

$$\phi = \phi_c - \beta L \tag{5}$$

where L is the transmission distance; therefore,

$$\phi = \phi_c - \beta_c L - D_1 L\,\Delta\omega - \tfrac{1}{2}D_2 L\,\Delta\omega^2 - \tfrac{1}{6}D_3 L\,\Delta\omega^3 - \tfrac{1}{24}D_4 L\,\Delta\omega^4 - \cdots \tag{6}$$

Equation (6) shows that the first two terms on the right-hand side are constant phase contributions and the third term corresponds to a pure time delay. In the analysis we neglect the demands of absolute phase and absolute time at the receiver side and analyze the phase contributions offered by second-, third-, and fourth-order terms of the propagation constant. We can compensate the dispersion effect by differential time delays of the upper and the lower sidebands. We might separate the upper and lower sidebands into two arms of an interferometer and apply different time delays in each arm before they are synchronously combined for further transmission or detection. Therefore, total phase deviation, figure of merit, and the dimension free chirp parameter were calculated for ideal and realistic optical systems using higher order dispersion terms individually.

Case 1: Using 2OD Term

In Eq. (6) neglecting demands of absolute phase and absolute time at the receiver side and considering only second-order dispersion term, the phase deviation can now be expressed as

$$\phi_2 = \frac{1}{2}D_2 L\,\Delta\omega^2 \tag{7}$$

The deviation in the time for arrival of frequencies can now be expressed as

$$\Delta t = -\frac{d\phi_2}{d\omega} = -D_2 L\,\Delta\omega \tag{8}$$

where $\Delta t = t - t_c$, t_c is the arrival time for the carrier frequency.

The time delay in the arms of the interferometer can be expressed as $(\pm C_2\,\omega_{cl} D_2 L)/2$ where C_2 is a dimension free parameter and ω_{cl} is the angular clock frequency of the system. The total phase deviation can now be expressed as

$$\begin{aligned}\phi_2(\text{total}) &= \phi_2 \pm (C_2\,\omega_{\text{cl}} D_2 L\,\Delta\omega)/2 \\ &= D_2 L(\Delta\omega^2 \pm C_2\,\omega_{\text{cl}}\,\Delta\omega)/2 \end{aligned} \tag{9}$$

where the plus sign is used for the lower sideband and the minus sign for the upper sideband.

The calculation of RMS value of the phase deviation is the most common way to measure the degradation in dispersive systems. For the proposed compensating device the RMS value has been calculated for higher order dispersion terms.

In general, the RMS value of the phase deviation for the compensating device is expressed as

$$\phi_{n\,\text{RMS}} = \left[\int_{\omega-\omega_{\text{cl}}}^{\omega+\omega_{\text{cl}}} \frac{P(\Delta\omega)(\phi_n(\text{total}))^2\,d\omega}{2\,\omega_{\text{cl}}}\right]^{1/2} \tag{10}$$

where $n = 1, 2, 3\ldots$ (order of dispersion term) and $P(\omega)$ is a dimension free weight function.

Using Eqs. (9) and (10) for $n = 2$

$$\phi_{2\,\text{RMS}} = \left[\int_{\omega-\omega_{\text{cl}}}^{\omega+\omega_{\text{cl}}} \frac{P(\Delta\omega)\left[D_2 L(\Delta\omega^2 \pm C_2\,\omega_{\text{cl}}\,\Delta\omega)/2\right]d\omega}{2\,\omega_{\text{cl}}}\right]^{1/2}$$

$$\phi_{2\,\text{RMS}} = \frac{D_2 L}{2\sqrt{\omega_{\text{cl}}}}\left[\int_0^{\omega_{\text{cl}}} P(\omega)(\omega^2 - C_2\,\omega_{\text{cl}}\,\omega)^2\,d\omega\right]^{1/2}$$

$$\phi_{2\,\text{RMS}} = \frac{D_2 L}{2\sqrt{\omega_{\text{cl}}}}\left[\int_0^{\omega_{\text{cl}}} (\omega^4 + C_2^2\omega_{\text{cl}}^2\omega^2 - C_2\,\omega_{\text{cl}}\,\omega)^2\,d\omega\right]^{1/2}$$

where, for the moment, $P(\omega)$ is a dimension free weight function and for analysis it is set to 1. Therefore,

$$\phi_{2\,\text{RMS}} = \frac{D_2 L}{2\sqrt{\omega_{\text{cl}}}}\left[\int_0^{\omega_{\text{cl}}} (\omega^4 + C_2^2\omega_{\text{cl}}^2\omega^2 - 2C_2\,\omega_{\text{cl}}\,\omega^3)\,d\omega\right]^{1/2}$$

Hence, at $\omega = \omega_{\text{cl}}$, $\phi_{2\,\text{RMS}}$ is found to be

$$\begin{aligned}\phi_{2\,\text{RMS}} &= \frac{D_2 L\,\omega_{\text{cl}}^2}{2}\left[\left(\frac{1}{5} + \frac{C_2^2}{3} - \frac{C_2}{2}\right)\right]^{1/2} \\ &= \frac{D_2 L\,\omega_{\text{cl}}^2}{2}\sqrt{\alpha} \end{aligned} \tag{11}$$

where

$$\alpha = \frac{1}{5} + \frac{C_2^2}{3} - \frac{C_2}{2} \tag{12}$$

Hence to minimize the RMS value of phase deviation, the value of C_2 in Eq. (12) should be a minimum.

Therefore, putting $d\alpha/dc = 0$, it follows that $C_2 = 3/4$. Hence the optimum value of the phase equation can be obtained by putting $C_2 = 3/4$ in Eq. (11)

$$\phi_{2\,\mathrm{RMS\,(opt)}} = \frac{D_2 L \omega_{\mathrm{cl}}^2}{2}\sqrt{1/80} \tag{13}$$

Further obtaining $\phi_{2\,\mathrm{RMS}}|_{C2=0}$, by putting $C_2 = 0$ in Eq. (11)

$$\phi_{2\,\mathrm{RMS}}|_{C2=0}\,\frac{D_2 L \omega_{\mathrm{cl}}^2}{2}\sqrt{\frac{1}{5}} \tag{14}$$

Finally, the figure of merit for the dispersion compensating device can now be obtained from Eqs. (13) and (14)

$$G_2 = \frac{\phi_{2\,\mathrm{RMS}}|_{C2=0}}{\phi_{2\,\mathrm{RMS}}|_{C2=3/4}} = \sqrt{\frac{80}{5}} = 4 \tag{15}$$

Equations (15) and (12) show that the figure of merit and optimum chirp parameter are found to be 4 and 3/4, respectively, using the second-order dispersion term when the weight function $P(\omega)$ is set to 1. Hence, this can be interpreted as, for an ideal case, that it is possible to double the bandwidth or quadruple the transmitting distance of an optical communication system without degrading signal quality, as mentioned in [13].

Case 2: Using 3OD Term

The phase deviation using only the third-order dispersion term can be expressed as (using Eq. (6))

$$\phi_3 = \frac{1}{6} D_3 L\, \Delta\omega^3$$

Therefore,

$$\Delta t = -\frac{d\phi}{d\omega} = -\frac{1}{2} D_3 L\, \Delta\omega^2 \tag{16}$$

Hence, time delay in the arms of the interferometer to be expressed as $\pm C_3 \omega_{\mathrm{cl}} D_3 L\, \Delta\omega/4$ and hence, the total phase deviation due to the third-order dispersion term can be expressed as

$$\begin{aligned}\phi_{3(\mathrm{total})} &= \phi_3 \pm (C_3 \omega_{\mathrm{cl}} D_3 L\, \Delta\omega^2)/4 \\ &= D_3 L (2\,\Delta\omega^3 \pm 3 C_3 \omega_{\mathrm{cl}}\, \Delta\omega^2)/12\end{aligned} \tag{17}$$

The RMS value of the phase deviation for the compensating device using Eqs. (17) and (10) for $n = 3$ can be expressed as

$$\phi_{3\,\mathrm{RMS}} = \left[\int_{\omega-\omega_{\mathrm{cl}}}^{\omega+\omega_{\mathrm{cl}}} \frac{P(\Delta\omega)\left[D_3 L(2\,\Delta\omega^3 \pm 3C_3\,\omega_{\mathrm{cl}}\,\Delta\omega^2)/12\right]^2}{2\,\omega_{\mathrm{cl}}}\,d\omega\right]^{1/2}$$

$$= \frac{D_3 L}{12\sqrt{\omega_{\mathrm{cl}}}}\left[\int_0^{\omega_{\mathrm{cl}}} P(\omega)(2\omega^3 - 3C_3\,\omega_{\mathrm{cl}}\,\omega^2)^2\,d\omega\right]^{1/2}$$

Assuming $P(\omega) = 1$, $\phi_{3\,\mathrm{RMS}}$ is found to be (at $\omega = \omega_{\mathrm{cl}}$)

$$\phi_{3\,\mathrm{RMS}} = \frac{D_3 L\,\omega_{\mathrm{cl}}^3}{12}\sqrt{\frac{4}{7} + \frac{9C_3^2}{5} - 2C_3} \tag{19}$$

From Eq. (19), the C_3 value (optimum) is 5/9 and therefore,

$$\phi_{3\,\mathrm{RMS}}|_{C3=\mathrm{opt}} = \frac{D_3 L\,\omega_{\mathrm{cl}}^3}{12}\sqrt{\frac{1}{63}} \tag{20}$$

$$\phi_{3\,\mathrm{RMS}}|_{C3=0} = \frac{D_3 L\,\omega_{\mathrm{cl}}^3}{12}\sqrt{4/7} \tag{21}$$

$$G_3 = \frac{\phi_{3\,\mathrm{RMS}}|_{C3=0}}{\phi_{3\,\mathrm{RMS}}|_{C3=\mathrm{opt}}} = \sqrt{\frac{257}{7}} = \sqrt{36} = 6 \tag{22}$$

Hence, at $P(\omega) = 1$, C_3 and G_3 values are found to be equal to 5/9 and 6, respectively, using only the third-order dispersion term. Again, this could be interpreted as, for an ideal case, that it is possible to sixfold the transmitting distance of an optical communication system without degrading signal equality.

Case 3: Using 4OD and Other Higher Order Terms

Once again, using Eq. (6)

$$\phi_4 = D_4 L\,\Delta\omega^4/24 \tag{23}$$

Therefore,

$$\Delta t = -\frac{d\phi}{dt} = -D_4 L\,\Delta\omega^3/6 \tag{24}$$

and, hence, the time delay in the arms of the interferometer can be expressed as $\pm C_4\,\omega_{\mathrm{cl}} D_4\,\Delta\omega^2/12$, where C_4 is the dimensionless chirp parameter.

The total phase deviation can now be expressed as

$$\phi_{4(\mathrm{total})} = \phi_4 \pm (C_4\,\omega_{\mathrm{cl}} D_4 L\,\Delta\omega^3)/12$$

$$= D_4 L(\Delta\omega^4 \pm 2C_4\,\omega_{\mathrm{cl}}\,\Delta\omega^3)/24 \tag{25}$$

Again using Eqs. (25) and (10) for $n = 4$, the RMS value of phase deviation for the compensating device can be expressed as

$$\phi_{4\,\mathrm{RMS}} = \left[\int_{\omega-\omega_{\mathrm{cl}}}^{\omega+\omega_{\mathrm{cl}}} \frac{P(\Delta\omega)\left[D_4 L(\Delta\omega^4 \pm 2C_4\omega_{\mathrm{cl}}\Delta\omega^3)/24\right]^2 d\omega}{2\omega_{\mathrm{cl}}}\right]^{1/2}$$

$$= \frac{D_4 L}{24\sqrt{\omega_{\mathrm{cl}}}}\left[\int_0^{\omega_{\mathrm{cl}}} P(\omega)\big[\omega^4 - 2C_4\omega_{\mathrm{cl}}\omega^3\big)^2 d\omega\right]^{1/2}$$

where $P(\omega)$ is a dimensionfree weight function and for the analysis it is set to 1.

$$\phi_{4\,\mathrm{RMS}} = \frac{D_4 L}{24\sqrt{\omega_{\mathrm{cl}}}}\left[\int_0^{\omega_{\mathrm{cl}}} (\omega^8 + 4C_4^2\omega_{\mathrm{cl}}^2\omega^6 - 4C_4\omega_{\mathrm{cl}}^7)\, d\omega\right]^{1/2} \tag{26}$$

$$\phi_{4\,\mathrm{RMS}} = \frac{D_4 L\omega_{\mathrm{cl}}^4}{24}\left(\frac{1}{9} + \frac{4C_4^2}{7} - \frac{C_4}{2}\right)^{1/2} \tag{27}$$

Similarly from Eq. (27) the minimum value of C is found to be $7/16$.

$$\phi_{4\,\mathrm{RMS}}|_{C4=\mathrm{opt}} = \frac{D_4 L\omega_{\mathrm{cl}}^4}{24}\sqrt{1/576} \tag{28}$$

$$\phi_{4\,\mathrm{RMS}}|_{C4=0} = \frac{D_4 L\omega_{\mathrm{cl}}^4}{24}\sqrt{1/9} \tag{29}$$

Using Eqs. (28) and (29) the value of G_4 is found to be

$$G_4 = \frac{\phi_{4\,\mathrm{RMS}}|_{C_4=0}}{\phi_{4\,\mathrm{RMS}}|_{C_4=\mathrm{opt}}} = \sqrt{\frac{576}{9}} = \sqrt{64} = 8 \tag{30}$$

Hence, from Eq. (30), it was found that at $P(\omega) = 1$, the values of C_4 and G_4 are $7/16$ and 8, respectively. Further, this can be interpreted as, for an ideal case, that is it possible to eightfold the transmitting distance of an optical communication system without degrading signal quality. Finally, from Eqs. (15), (22), and (30), it has been analyzed that the figure of merit and dimension free chirp parameter for any order of dispersion term can be calculated from the formulae

$$G_n = 2n$$

$$C_n = (2n - 1)/n^2$$

where $n = 1, 2, 3, \ldots$ (order of dispersion term).

Results and Discussion

The analysis in the previous section shows that the higher figure of merit can be obtained for the dispersion-compensating device if the dispersion compensation has been done by incorporating higher order dispersion terms. In comparison to other dispersion-compensation techniques [3, 5, 8, 10–12], it is possible to increase the transmitting distance of an optical communication system. For an ideal case (i.e., when the weight function $P(\omega) = 1$), it was analyzed that the figure of merit is found to be 4, 6, and 8, when 2OD, 3OD, and 4OD terms are included in the analysis of the dispersion-compensating device, respectively.

However, the ideal case (when $P(\omega) = 1$) requires a "sinc" as the pulse envelope, which is not possible to maintain throughout in the realistic systems. Therefore, for the realistic systems the weight function $P(\omega)$ is taken to be a continuous function where $P(0) = 1$ and $P(\pm\omega_{cl}) = 0$. In Table 1, the figure of merit and dimension free chirp parameter (for dispersion-compensating device) was obtained using some simple realistic weight functions $P(\omega)$. These realistic weight functions (in Table 1) were chosen to compare the values of figure of merit (G_3, G_4) and dimension free chirp parameter (C_3, C_4) of the dispersion-compensating device for 3OD and 4OD terms in addition to 2OD terms as reported in [13]. Table 1 shows that for higher order dispersion terms in the compensating device (using differential time delay technique) the figure of merit increases whereas the dimension free chirp parameter decreases. Hence, it is possible to enhance the transmitting distance of an optical communication system without degrading signal quality when a dispersion-compensation device uses higher order dispersion terms.

Implementation Scheme

The dispersion-compensation technique analyzed here can be implemented either using discrete devices or integrated optical circuits in materials as discussed in [6, 13–16].

In the first scheme an incoming signal is split by a 3-dB splitter and each branch uses an optical narrowband filter (fiber Fabry–Perot filter) as depicted in Figure 1. The bandwidth is chosen so as to allow only the upper or lower modulation sideband to pass through. The sideband of one of the branches was delayed by time T relative to other sideband in order to compensate for the different propagation times in the dispersive fiber. A delay of 100 ps can be obtained using 2 cm of extra fiber length in one branch. The signals are then recombined (in phase) in a combiner. In a real implementation, it was proposed to use an active phase control since the optical path length tolerance is of the order of 10% of the wavelength in the waveguide.

Table 1

$P(\omega)$ Weight Functions	For 2OD Term C_2	For 2OD Term G_2	For 3OD Term C_3	For 3OD Term G_3	For 4OD Term C_4	For 4OD Term G_4
1(Ideal Case)	0.75	4.0	0.55	6.0	0.43	8.0
$1 - \left\lvert \frac{\omega}{\omega_{cl}} \right\rvert$	0.60	3.2	0.48	4.6	0.39	6.1
$\mathrm{Cos}^2\left(\frac{\pi\omega}{2\omega_{cl}}\right)$	0.53	3.0	0.43	4.3	0.35	5.9
$\frac{10}{9}\mathrm{Cos}^2\left(\frac{\pi\omega}{2\omega_{cl}}\right) - \frac{1}{9}\mathrm{Cos}^2\left(\frac{3\pi\omega}{2\omega_{cl}}\right)$	0.48	3.1	0.39	4.2	0.32	6.1

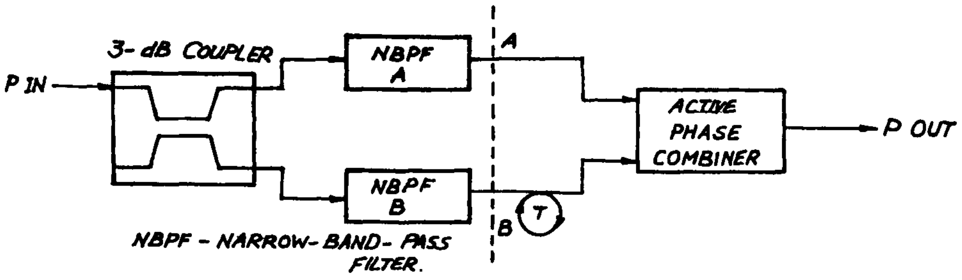

Figure 1. Schematic figure showing the principle of dispersion by using splitting, filtering, delay, and recombination. The "A" and "B" design of the two different branches, each one containing one of the modulated sidebands.

Secondly, integrated optical implementation using a single-mode waveguide could be considered. The implementation of narrowband filters and phase control could be done using resonant laser (DFB or DBR), and the phase control could be implemented by introducing a short (tenth of a millimeter length) forward- or reverse-biased phase modulator section. The required delay times T could be implemented with relatively short waveguide section (around 10 mm for $T = 100$ ps). Polarization is the main problem in this method and it is very difficult to fabricate integrated, extremely narrowband polarization-independent filters. Therefore, it needs active polarization control or polarization-spreading technique.

The third way to realize the dispersion-compensation scheme could be a Mach–Zehnder interferometer as shown in Figure 2. An advantage of this method is that it avoids the power loss due to the filters and it can be realized using lithographic technology, leading to potentially low fabrication costs. Also, by designing a squared waveguide cross section, this can be made polarization-insensitive [17]. The input signal is split into two equal parts by a 3-dB coupler. The two versions of the same signal traverse paths of slightly different lengths and merge together in another 3-dB coupler at the output. The resonant condition of the Mach–Zehnder interferometer is obtained using tuning control to achieve wavelength periodicity, causing a higher modulation sideband to exit in "A" as shown in Figure 2 and the lower modulation sideband in "B". Finally, one sideband is delayed and signals are recombined as shown in Figure 1.

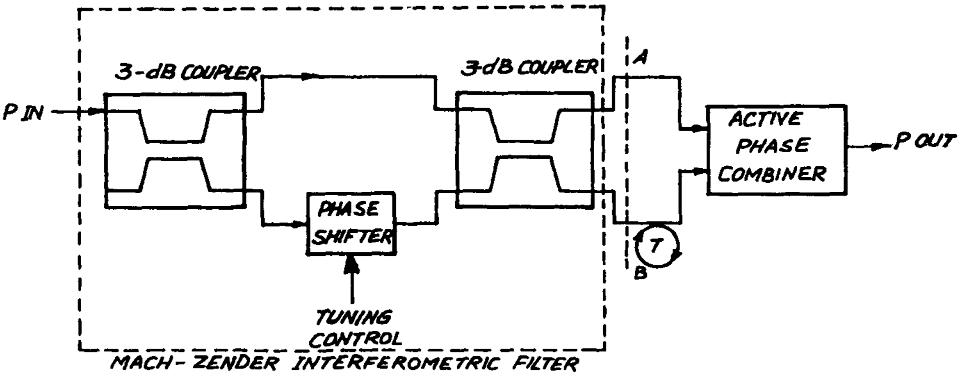

Figure 2. Schematic figure showing the principle of dispersion compensation using a Mach–Zehnder interferometer in order to split the upper and lower modulation sidebands.

The advantages of the dispersion-compensation technique analyzed here is that it can be implemented in the form of small (of the order of 10 mm) integrated photonic circuits, integrated with laser amplifiers and detectors. An interesting option would be to include not only one but several different delay lines on the same chip corresponding to different fiber lengths (transmission distance). In future flexible, transparent photonic networks, which employ space and wavelength routing for functions like protection switching, the fiber length will not be predetermined at the time of installation. The inclusion of several delay lines on the dispersion-compensation chip would require that a space-switching function be included on the chip, and this can be realized in many ways.

Conclusion

In this paper we presented the detailed theoretical analysis for the dispersion-compensating device using differential time delay for higher order dispersion terms. A dispersion-compensating device based on this technique was analyzed and results were obtained for the ideal and realistic weight functions of the systems. Further, a comparison was done between ideal and realistic systems. In both cases the results show that the dispersion compensation using higher order dispersion terms presents higher figure of merit and lower dimension free chirp parameter for the compensating device. Hence, long-span optical transmission (ideally, fourfold, sixfold, and eightfold transmission for 2OD, 3OD, and 4OD, respectively) can be obtained using the compensating device based on this technique.

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