Contributed paper

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Impact of frequency response of two-segment semiconductor laser on dispersion supported transmission with a binary optical signal at the receiver

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Analysis of impact of frequency response of two-segment DFB laser on conversion of a frequency-modulated signal to amplitude modulation through dispersion in an optical fibre is presented. A novel modulation scheme that produces a binary optical signal at the fibre output is used. This new scheme is based on the linear frequency modulation along with the Manchester coding. A 5 Gb/s optical transmission system is presented; it uses the new method of FM-AM conversion supported transmission. The propagation of optical field through a fibre is described by nonlinear Schrödinger equation, which is solved numerically by the split-step Fourier method.

Keywords: semiconductor lasers, optical fibre dispersion, dispersion supported transmission, optical communications.

1. Introduction

The dispersion supported transmission (DST) is based on the conversion of laser FM to optical AM at the receiver due to the fibre chromatic dispersion. This principle has been known since 1981 [1], however, it was not until early nineties that the first experimental DST systems were presented [2]. Since then a few modifications of such systems have been proposed, including combined AM/FM modulation at the transmitter [3], multilevel signal format [4], and the so called DIMENSION transmission [5]. However, even for the binary modulation the optical signal at the receiver has three or four levels [2]. The conversion to binary signal requires either multilevel decision [6] or low-pass filtering. This, in turn, leads to the receiver complication and/or closing of the eye pattern. In Ref. 7 we presented a modulation scheme that produces a binary optical signal at the fibre output. Here, we investigate impact of frequency response of two-segment DFB laser on our modulation scheme that produces a binary optical signal. The analysis makes it possible to observe the influence of laser frequency response on FM to AM conversion and shape of the received pulses.

2. Theory

Let us assume that the frequency modulated optical signal is

$$\psi(t) = A\,\mathrm{Re}(\exp[j\phi(t)]), \tag{1}$$

where A is the amplitude of the signal and ϕ is the phase of this signal.

If the optical signal is generated by semiconductor injection laser driven with the dc current I_0, the frequency modulation can be achieved by adding the short-time varying signal current (I_m) to the dc bias. The total drive current assumes the form

$$I = I_0 + I_m. \tag{2}$$

Ideally, the frequency modulation would be proportional to the modulation current

$$f_d(t) = K I_m(t). \tag{3}$$

In the time domain, the phase of the optical signal can be written as

$$\frac{\phi(t)}{2\pi} = K\int_0^t I_m(t) * H_v(t)dt. \tag{4}$$

In Eq. (4), the symbol * denotes convolution.

The constant K in Eqs. (3) and (4) is given by

$$K = \frac{f_{d,\max}(t)}{I_{m,\max}(t)}, \tag{5}$$

where f_d is the value of frequency deviation, $f_{d,max}$ is the maximum value of frequency deviation, $I_{m,max}$ is the value of the current for $f_d = f_{d,max}$ and H_v is the laser frequency response.

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The convolution in the time domain is equivalent to the multiplication in the frequency domain and the integral in the time domain is equivalent to the multiplication operator 1/jω in the frequency domain. Thus Eq. (4) can be rewritten as

$$\frac{\phi(t)}{2\pi} = K\Im^{-1}\left\{\Im[I_m(t)]\frac{H_V(j\omega)}{j\omega}\right\}, \quad (6)$$

where $\Im$ is the Fourier transform and $\Im^{-1}$ is the inverse Fourier transform.

Performing the small-signal analysis (presented in Ref. 8), we obtain the following expressions for the normalised form of frequency response of the laser [10]

$$H_V(j\omega)\left|\frac{\Omega_d\omega_r^2}{\Omega_d\Omega_c - Q_1\omega_r^2}\right|\frac{(\Omega_d + j\omega)(\Omega_c + j\omega) - Q_1\omega_r^2}{(\Omega_d + j\Omega_V)(\omega_r^2 - \omega^2 + j\omega\Omega)}, \quad (7)$$

with

$$\Omega_d = \frac{1}{\tau} + (1 - \chi\tau_p^2\omega_r^2)\tau_p\omega_r^2, \quad (8)$$

$$\Omega_c = \chi\tau_p\omega_r^2, \quad (9)$$

$$\Omega = \Omega_d + \Omega_c. \quad (10)$$

Here τ_p is the photon lifetime in the cavity, τ is the carrier lifetime, ω_r is the relaxation resonance angular frequency, Q_1 is the tuning parameter and χ is the gain compression coefficient.

The tuning parameter Q_1 of a laser consisting of the two-segments of the lengths L_1 and L_2 is defined, as follows [10]

$$Q_1 = \frac{r_1q_2 - r_2q_1}{q_1}\frac{1 - 2\chi\tau_p^2\omega_r^2}{r_2 + r_1\dfrac{G_1}{G_2}}, \quad (11)$$

where

$$r_i = \frac{L_i}{L_1 + L_2} \quad i = 1,2. \quad (12)$$

The sign of the tuning parameter Q_1 determines whether the frequency shift in response to an increase of the laser's drive current is positive (blue shift) or negative (red shift). If $Q_1 < 0$ then blue shift occurs, if $Q_1 > 0$ red shift occurs. The single-section frequency response is characterised by Eq. (7) when $Q_1 = 0$. The propagation through the optical fibre is described by the propagation term $\exp(-j\beta L)$ with the length L of the transmission fibre and the phase constant β (losses are neglected).

Performing a Fourier transform the FM to AM the conversion factor (Ψ_{F-A}) can be calculated as

$$\Psi_{F-A}(t,L) = \int_{-\infty}^{\infty}\frac{d\omega}{2\pi}\exp(-j\beta L)\exp(j\omega t)\times \int_{-\infty}^{\infty}d\tau\cos[\phi(\tau)]\exp(-j\omega\tau). \quad (13)$$

Eq. (13) yields

$$\Psi_{F-A}(t,L) = \int_{-\infty}^{\infty}d\tau\int_{-\infty}^{\infty}\frac{d\omega}{2\pi}\cos[\phi(\tau)]\times \exp(-j\beta L)\exp[j\omega(t-\tau)]. \quad (14)$$

The phase constant β is given by

$$\beta = \beta_0 + (\omega - \omega_0)\beta_1 + \frac{1}{2}(\omega - \omega_0)^2\beta_2 + \ldots. \quad (15)$$

Here, the first and the second term correspond to the signal phase and delay, respectively. The third term is responsible for chromatic dispersion. We neglect for convenience, the phase and group delay because both terms produce only a phase delay of the carrier signal and a time delay of modulation signal and have no influence on the distortion of the signal.

According to Eqs. (14) and (15) the conversion factor can be rewritten as

$$\Psi_{F-A}(t,L) = \frac{1}{2\pi}\int_{-\infty}^{\infty}d\tau\cos[\phi(\tau)]\times \int_{-\infty}^{\infty}d\omega\exp\left(-j\omega^2\beta_2\frac{L}{2}\right)\exp[j\omega(t-\tau)]. \quad (16)$$

Because $\cos[\phi(\tau)] = \{\exp[j\phi(\tau)] + \exp[-j\phi(\tau)]\}/2$, Eq. (16) may be expressed via

$$\Psi_{F-A}(t,L) = \frac{1}{4\pi}\sqrt{\frac{2\pi}{j\beta_2 L}}\exp\left(-j\frac{t^2}{2\beta_2 L}\right)\times \left\{\int_{-\infty}^{\infty}d\tau\exp[j\phi(\tau)]\exp\left(-j\frac{\tau^2}{2}\frac{1}{\beta_2 L}\right)\exp\left(j\tau\frac{t}{\beta_2 L}\right) + \int_{-\infty}^{\infty}d\tau\exp[-j\phi(\tau)]\exp\left(-j\frac{\tau^2}{2}\frac{1}{\beta_2 L}\right)\exp\left(j\tau\frac{t}{\beta_2 L}\right)\right\}. \quad (17)$$

Knowing the form of $\phi(\tau)$ we are able to calculate the output signal at the receiver.

3. Principle of dispersion supported transmission system operation

Instead of the binary frequency modulation of the transmitter we proposed a linear frequency modulation with the differential Manchester coding [7]. For a standard fibre in the 1.55 μm window, the logical "–1" corresponds to the linear frequency increase and the logical "1" corresponds to the similar frequency decrease as shown in Fig. 1. Such a signal form may be readily obtained by a proper integration of

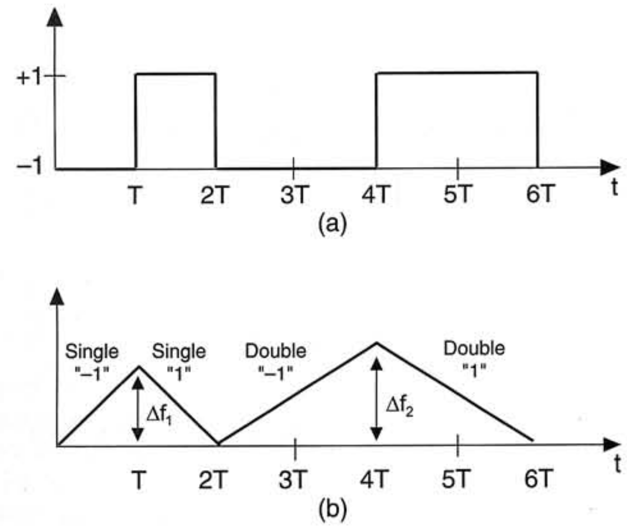

Fig. 1. Principle of signal modulation

binary data. According to the differential Manchester coding principle both the symbols "–1" and "1" could last only for T (100 ps) and 2T (200 ps). The $\omega_{d,max,1}$ (for T) and $\omega_{d,max,2}$ (for 2T) need not be equal to each other. We have found that the optical signal at the receiver has the best properties (in terms of high value of the extinction coefficient, the signal to noise ratio and the binary optical output signal) when the values of $\omega_{d,max,1}$ and $\omega_{d,max,2}$ vary according to Fig. 2. Then, the signal powers corresponding to T and 2T periods are the same [7]. The angular frequency deviation $\omega_{d,max,1}$ is related to the system parameters via

$$\omega_{d,\max,1} = 0.5\frac{Tc}{LD\lambda^2}, \tag{18}$$

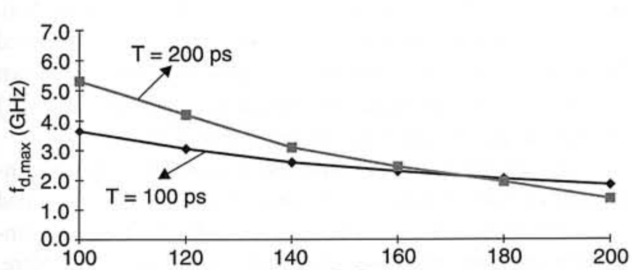

Fig. 2. Change of the optical frequency $f_{d,max,1}$ and $f_{d,max,2}$ vs. fibre length.

where D is the dispersion coefficient, c is the speed of light in vacuum, λ is the wavelength and L is the fibre length.

4. Simulations and results

The computer simulation is carried out for a system (Fig. 3) with the following characteristics.

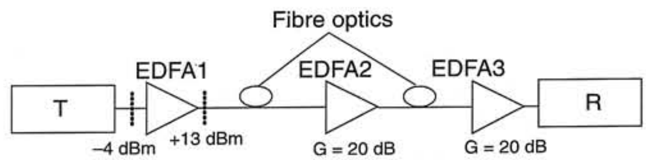

Fig. 3. Experimental setup of 5 Gbit/s optical transmission system. T is the transmitter, R is the receiver, and G is the amplifier gain.

The laser frequency response determined by Eq. (7) is computed for three values of tuning parameter: $Q_1 = -1$ (two-segment laser, blue shift), $Q_1 = 0$ (single-section laser), and $Q_1 = 0.2$ (two-segment laser, red shift); we also investigated the frequency response of an ideal laser (unit frequency response). In our simulations, the values of the carrier lifetime, the photon lifetime in the cavity, and the relaxation resonance frequency are chosen as: $\tau = 1$ ns, $\tau_p = 2$ ps and $f_r = 5$ GHz, respectively [10]. The optical source is assumed to produce frequency modulated 5 Gbit/s signal with the differential Manchester format. The transmitted signal is modulated by 2^7–1 pseudorandom sequence and the optical frequency is shown in Fig. 2. The fibre dispersion is 17 ps/nm·km, the average loss is 0.2 dB/km. Optical in-line amplifier (EDFA2) is inserted at 100 km. The gain of the amplifier (G = 20 dB) is selected to compensate for the fibre loss. When the in-line amplifier is used it can be assumed that its spontaneous emission contributes insignificantly to the total noise. The receiver consists of PIN-detector, followed by the first order Butterworth filter. The Butterworth filter response is given by

$$H_{FR}(j\omega) = \frac{1}{\sqrt{1+\left(\dfrac{\omega}{\omega_R}\right)^2}}, \tag{19}$$

where ω is the angular frequency and ω_R is the filter bandwidth.

For the medium lengths L < 120 km, amplifiers EDFA1 and EDFA3 are employed. For the larger lengths (L > 140 km), EDFA2 is inserted at 100 km. The computer simulation is only carried out for fibre length equal to 160 km and $\omega_{d,max,1} = 2\pi\times2.3$ GHz for T = 100 ps, and $\omega_{d,max,2} = 2\pi\times2.45$ GHz for T = 200 ps. The propagation of the optical field through a fibre is described by the nonlinear Schrödinger equation, which was solved numerically by the split & step Fourier method [11].

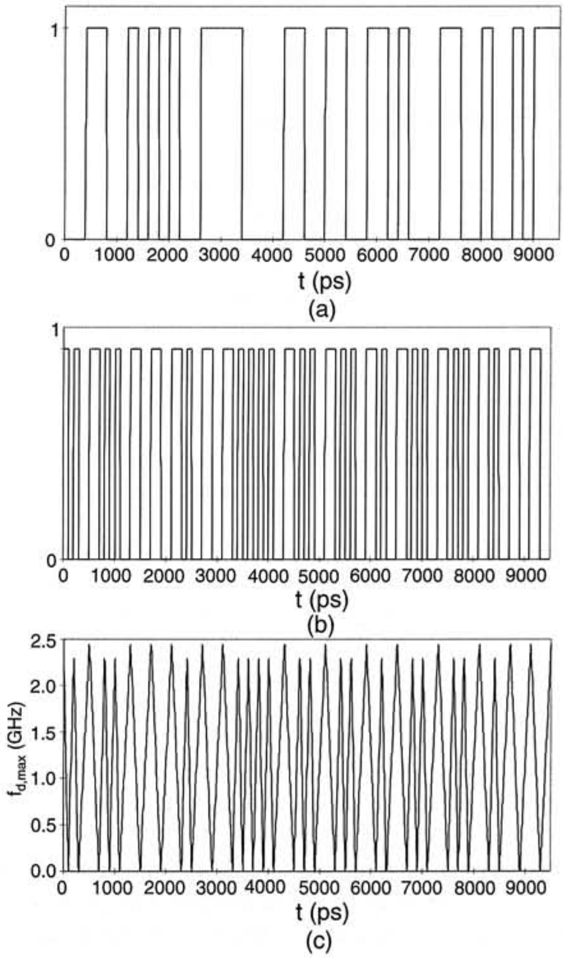

Fig. 4. Pseudorandom sequence of data (a), Manchester code (b), modulation frequency (c).

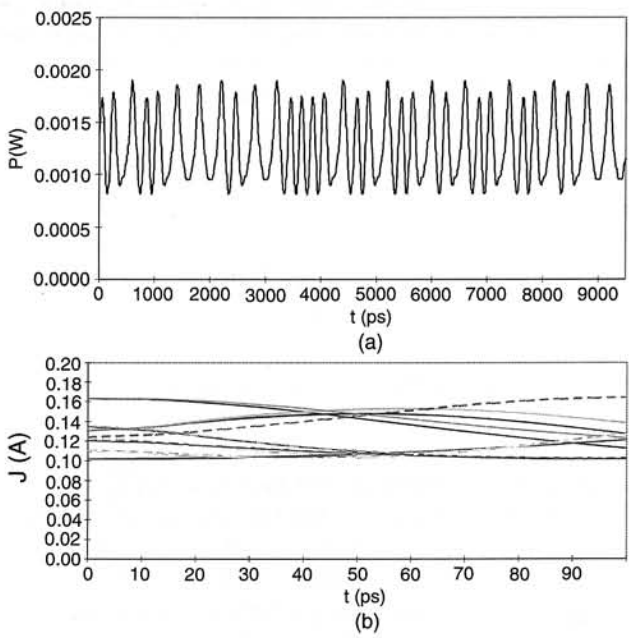

Fig. 5. Optical signal power at the receiver unit frequency response ($H_\nu = 1$) (a), eye diagram at the receiver for unit frequency response ($H_\nu = 1$) (b).

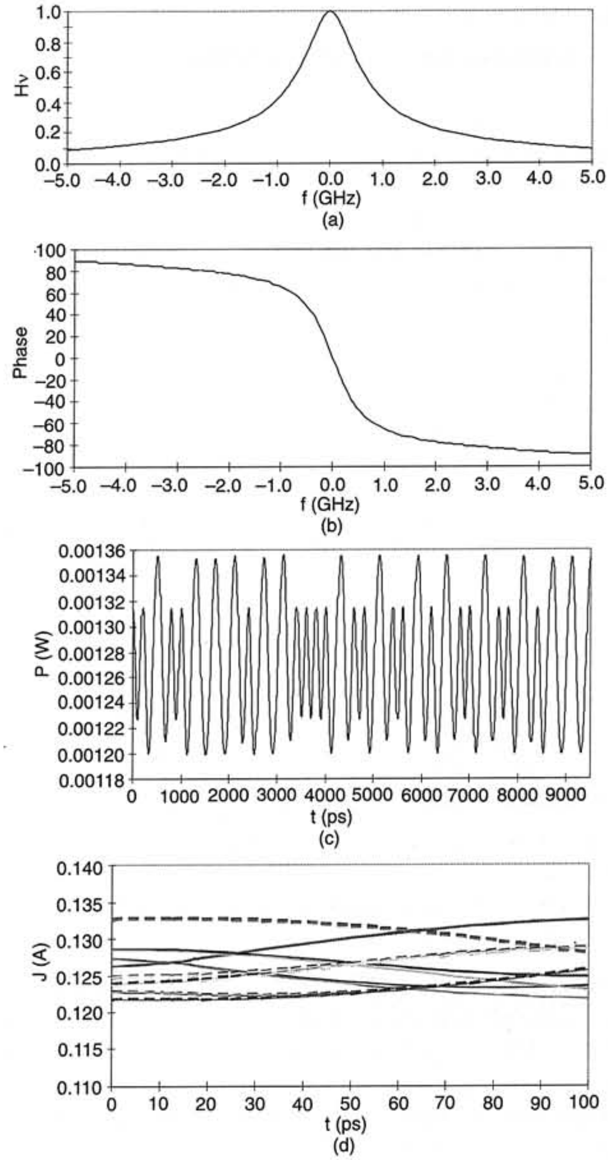

Fig. 6. Laser frequency response for $Q_1 = -1$ – amplitude (a), laser frequency response for $Q_1 = -1$ – phase (b), optical signal power at the receiver for $Q_1 = -1$ (c), eye diagram at the receiver for $Q_1 = -1$ and f_R = 5 GHz (d).

We show in Figs. 4(a), 4(b), and 4(c) the data, differential Manchester code and modulating frequency, respectively. The optical signal power at the receiver for ideal laser (unit frequency response: $H_\nu = 1$) is shown in Fig. 5(a). The eye diagram at receiver for unit transfer function and the Butterworth filter bandwidth equal to 5 GHz is shown in Fig. 5(b). For an ideal laser frequency response ($H_\nu = 1$) the optical pulses are least distorted [see Fig. 5(b)].

The simulation shows that the maximum value of amplitude of laser frequency response for $Q_1 = -1$ is reached at f = 0 GHz [see Fig. 6(a)]. For $f \neq 0$ GHz the value of amplitude of laser response decreases symmetrically. Here, the phase is equals 0° near f = 0 GHz and approach –90° for large positive values of the modulation frequency [Fig. 6(b)]; the cosine of the phase, which is proportional to real

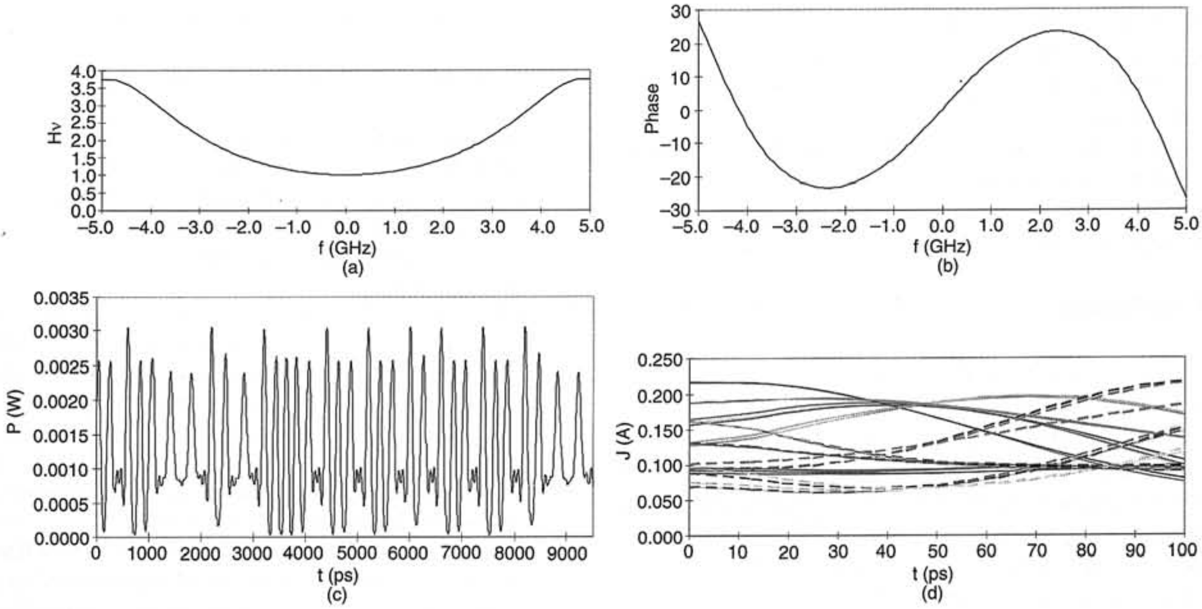

Fig. 7. Laser frequency response for $Q_1 = 0$ – amplitude (a), laser frequency response for $Q_1 = 0$ – phase (b), optical signal power at the receiver for $Q_1 = 0$ (c), eye diagram at the receiver for $Q_1 = 0$ and $f_R = 5$ GHz (d).

part of the frequency response, is always positive. Single-section laser is characterised by $Q_1 = 0$ and has laser frequency response shown in Fig. 7(a) (amplitude) and Fig. 7(b) (phase). Minimum of this amplitude is reached at the frequency modulation f = GHz. For f = 0 GHz the values of amplitude increases rapidly. For the frequency f = 0 GHz the phase equals to 0° and it changes from near –30° to near 30° between –5 GHz to 5 GHz. In the case of $Q_1 = 0.2$ the value of amplitude of laser frequency response is equals 1 for f = 0 GHz. The amplitude changes in depend on frequency as it is shown in Fig. 8(a). Here, the phase of laser frequency response starts at 180° at f = 0 GHz, so that cosine of the phase is equal –1, making the real part of the frequency response negative. A sign reversal occurs when the phase angle passes through 90° [Fig. 8(b)].

The optical pulses shape for: ideal laser, $Q_1 = -1$, $Q_1 = 0$ and $Q_1 = 0.2$ are shown in Fig. 5(a), 6(c), 7(c) and 8(c), respectively. The simulated eye patterns for: ideal laser, $Q_1 = -1$, $Q_1 = 0$ and $Q_1 = 0.2$ are shown in Fig. 5(b), 6(d), 7(d) and 8(d), respectively. These figures show the impact of the laser frequency response on optical pulses, which are produced by the conversion of laser FM to optical AM due to the fibre chromatic dispersion. By comparing Fig. 5(b) and other results [Fig. 6(d), 7(d), and 8(d)], we can observe that eye pattern is degraded by the laser frequency response. The interaction between the laser fre-

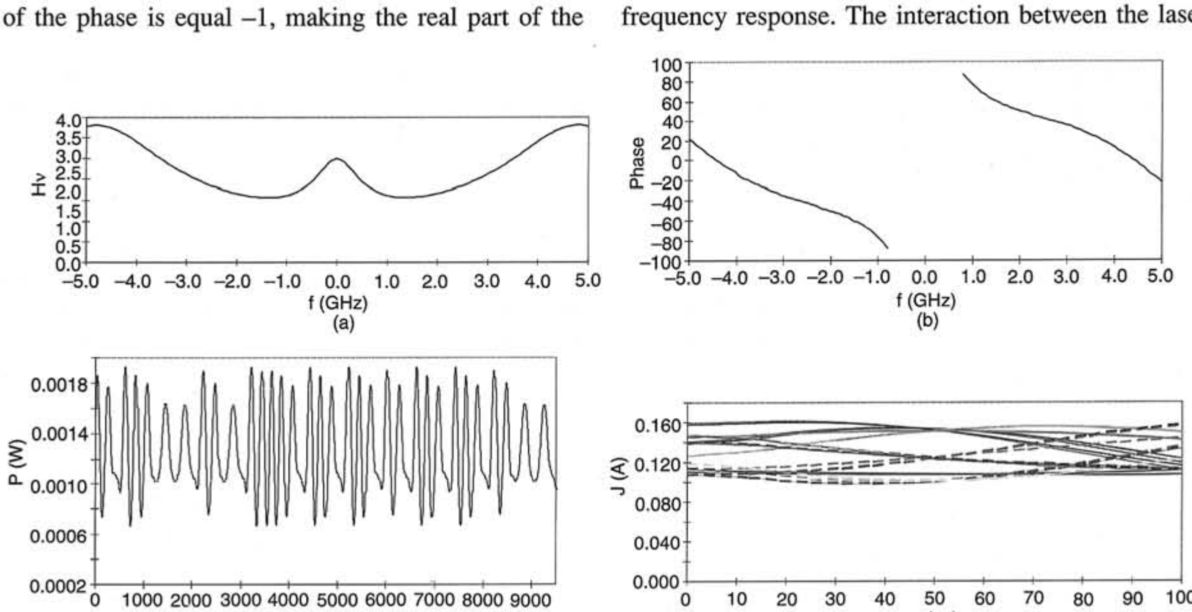

Fig. 8. Laser frequency response for $Q_1 = 0.2$ – amplitude (a), laser frequency response for $Q_1 = 0.2$ – phase (b), optical signal power at the receiver for $Q_1 = 0.2$ (c), eye diagram at the receiver for $Q_1 = 0.2$ and $f_R = 5$ GHz (d).

quency response and conversion of the frequency modulated signal to amplitude modulation causes the optical pulse distortion. By comparing Fig. 5(b), 6(d), 7(d), and 8(d) we conclude that for the value of $Q_1 \leq 0$, the phase of the frequency response causes the most of the pulse distortion. But this conclusion cannot be generalised, since the distortion depends on the particular choice of the parameter values [see Eq. (7)].

5. Conclusion

We have investigated the impact of the frequency response of two-segment DFB laser on dispersion supported transmission with a binary optical signal at the receiver. We have described a numerical simulation of frequency modulation of a single-section and a two-segment laser using small signal analysis derived in Ref. 8. The direction of the frequency shift is governed by the phase of the frequency response. Numerical simulations show that this effect deteriorates the eye opening at the receiver. Thus the frequency characteristic of the transmitter laser should be corrected possibly by preequalisation of the modulating signal.

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