Contributed paper

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Characterization of semiconductor laser frequency chirp based on signal distortion in dispersive optical fiber

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In the paper, the simple method of laser chirp parameters estimation is presented. It is based on measuring time-domain distortions of chirped signal transmitted through dispersive fiber and finding laser chirp parameters by matching measured distortions to calculated ones. Experiments undertaken with 1.55 µm telecommunication grade distributed feedback (DFB) lasers and standard single-mode fiber are described, together with some practical remarks on measurement setup and main conclusions.

Keywords: laser frequency chirp, laser parameters estimation, laser direct modulation.

1. Introduction

Frequency chirping of directly modulated semiconductor laser in interaction with chromatic dispersion causes distortions of the signal travelling along the optical fiber. These distortions are the main factors limiting the bit rate in medium and long-haul transmission systems based on standard single-mode fiber in 1.55-µm window. Various methods to overcome this limit were developed and widely used in wide area networks (WANs). In general, the laser chirp may be eliminated by applying the external modulator, or the dispersion may be reduced (compensated), or the transmission span may be divided by regenerators into the shorter ones.

The development of high-capacity metropolitan area networks (MANs) that are less demanding in terms of transmission distance, but strongly cost-sensitive, attracts the designers attention to high-speed, directly modulated transmitters working in standard fiber based networks. Additionally, very cost effective but limited in number of channels coarse wavelength division multiplexing (CWDM) calls for the highest possible data rate in each channel.

In such a situation, the precise knowledge about transmitter chirping performance is essential for successful design. Unfortunately, laser vendors usually do not specify chirp parameters. In the paper, the accurate and relatively simple measurement method of determining the laser chirp characteristics is described.

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2. Laser frequency chirp and its interaction with fiber dispersion

Direct intensity modulation leads to some variation of carrier concentration in the laser active region, what affects the refractive index and so frequency of a generated optical signal. Thus, the laser intensity modulation leads to (usually undesired) frequency chirp. The chirp of single-frequency laser may be described by the following equation [1]

$$\Delta\nu(t) = \frac{\alpha}{4\pi}\left(\frac{d}{dt}[\ln(P_L(t)) + \kappa P_L(t)]\right), \tag{1}$$

where $\Delta\nu(t)$ is the instantaneous frequency deviation, α is the so-called line enhancement factor, κ is the adiabatic chirp coefficient, and $P_L(t)$ is the laser output power. First term in the above equation, proportional to derivative of the logarithmed output power is called the transient chirp, and the second, directly proportional to the power, is the adiabatic chirp. It should be mentioned that Eq. (1) was derived for the Fabry-Perot (FP) lasers, but it is widely used as useful approximation for DFB ones [2–6]. For very low modulation frequency, the chirp induced by temperature variations of the laser chip may be also observed but this effect is not essential for high-speed laser transmitters.

To investigate the impact of chirp on a transmitted signal, the concepts of a signal complex envelope and a fiber impulse response [7] are useful. The complex envelope of optical field at the laser output is

$$E_L(t) = \sqrt{P_L(t)}\exp[j\phi_L(t)], \tag{2}$$

where $P_L(t)$ is the laser output power and $\phi_L(t)$ is the integral of a laser frequency deviation

$$\phi_L(t) = 2\pi \int_0^t \Delta\nu(t)dt. \tag{3}$$

The fiber impulse response may be written in the form

$$h(t) = \sqrt{j \frac{c}{zD\lambda^2}} \exp\left(-j \frac{\pi c}{zD\lambda^2} t^2\right), \tag{4}$$

where z is the fiber length, and D is the dispersion coefficient, defined as $d(1/\nu_g)/d\lambda$, λ is the centre wavelength of an optical signal and c is the light velocity in a vacuum. In the above equation, terms concerned with fiber attenuation and delay are neglected, as they do not influence the signal shape and are out of our interest.

The output signal complex envelope can be obtained by convolution of input envelope with fiber impulse response. The output power is square of output envelope absolute value, i.e.

$$P_O(t) = \left|E_L(t) * h(t)\right|^2. \tag{5}$$

In Fig. 1, some illustration of interaction of a laser chirp with fiber dispersion is presented. In Fig. 1(a), only adiabatic chirp is present. Simultaneously with increase in optical power, the laser frequency increases proportionally. When the fiber dispersion coefficient is positive (as in standard fiber for 1.55 μm window), this leads to increase in group velocity of subsequent pieces of signal rising edge. Thus, the output pulse rises faster than input, and even some overshoot may occur. Analogously, the subsequent pieces of falling edge travel the fiber slower than previous one, so the output falling edge is extended. In Fig. 1(b), only a transient chirp is taken into account, so frequency deviations occur only at the slopes of the pulse. The rising edge propagates faster than the flat part of the pulse, and falling one propagates slower. In consequence, both pulse edges are spread out of its central part. Figure 1(c) shows the combined impact of transient and adiabatic chirp. It is worth to be noticed that because the transient chirp is proportional to derivative of the logarithmed pulse power, it is strongly sensitive to the actual shapes of the pulse slopes, so the distorted output waveforms may be considerably different for supposedly similar input ones.

3. Chirp parameters characterization techniques

Some different methods of chirp parameters estimation are described in literature. One of them is based on time resolved chirp measurement setup shown schematically in Fig. 2.

The laser is large signal modulated by periodic waveform or pseudo random bit sequence (PRBS). One part of the output optical signal is directly measured by a high-speed digital sampling oscilloscope (DSO), second is passed through some optical frequency discriminating device, as Mach-Zhender interferometer or Fabry-Perot filter operating at the slope of its attenuation-versus-frequency

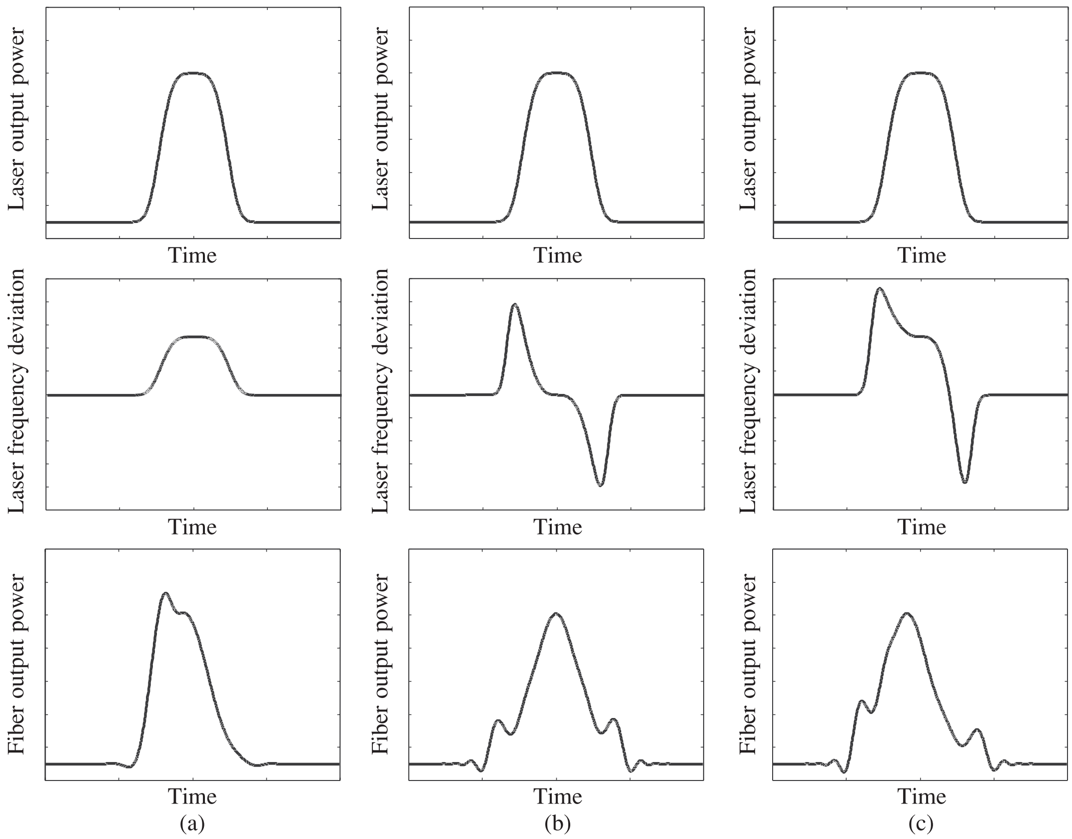

Fig. 1. Illustration of chirp-dispersion induced pulse distortion for: adiabatic (a), transient (b), and both chirp components (c).

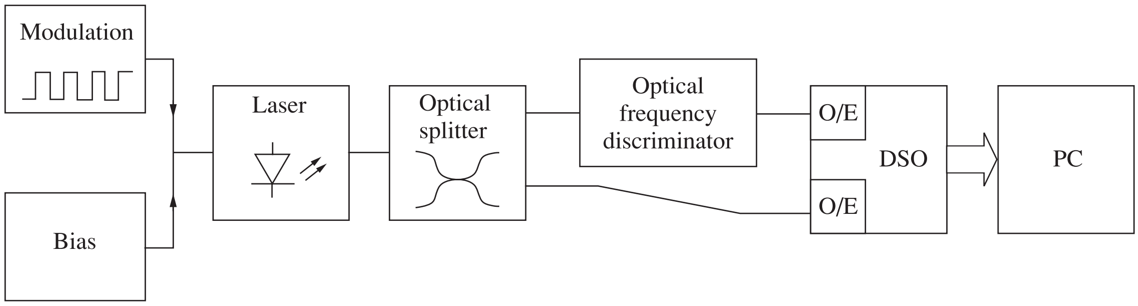

Fig. 2. Time resolved chirp measurement setup.

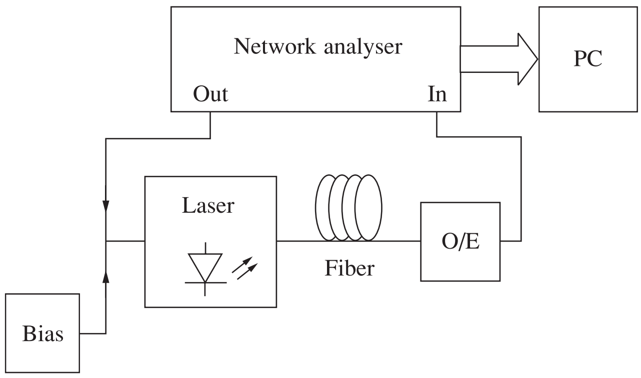

Fig. 3. Fiber transfer function measurement setup.

characteristic. Taking two registered signals and knowing the discriminator efficiency, the time resolved frequency deviation may be calculated. Desired laser parameters may be obtained by fitting frequency deviation obtained from Eq. (1) with the measured one. Practical realizations of this idea may be found in several papers, e.g., in Refs. 8 and 9.

Different method is based on measuring small signal intensity modulation transfer function of dispersive fiber with the laser under a test used as an optical source (Fig. 3).

Because the fiber dispersion introduces a frequency modulation (FM) to intensity modulation (IM) conversion, the laser chirp affects the measured transfer function and so the chirp parameters may be obtained when the fiber dispersion coefficient and length are known [10,11].

Dispersive fiber may also be used for laser chirp characterization in time-domain measurements. The modulated power waveform is measured both at the laser output and the fiber output. Knowing the laser output waveform and the fiber dispersion coefficient, the fiber output may be calculated using Eqs. (1–5). The chirp parameters may be found by fitting the calculated fiber output to the measured one. This method, to the author's knowledge, is investigated in less extend, thus its experimental verification with respect to nowadays DFB 1.55 µm telecommunication grade lasers will be presented below.

4. Measurements

The basic measurement setup is shown in Fig. 4. The laser under test is biased by a current source and modulated from a signal generator. The optical power waveform is measured both directly at the laser output and at the standard single-mode fiber output using HP 83480A DSO with HP 83485B optical-input plug-in unit.

As mentioned above, the chirp parameters may be obtained by finding the best agreement between calculated and measured fiber output waveforms. The matter is somehow complicated by the fact that fitting procedure involves not only the desired chirp parameters (that affect the measured waveform shape) but also the optical path attenuation and delay that affect the output waveform magnitude and its time-domain position on the scope. Although the fiber attenuation may be considered as a constant and well defined, the optical connectors losses are difficult to determine and unrepeatable during reconnections. The undertaken experiments shown than even 0.1 dB inaccuracy in the taken attenuation value may affect the chirp parameters estimation, thus the attenuation should be treated as another fitting parameter. Also the accurate time-domain shift should be applied to the calculated (or measured) waveform to reach overlap of these waveforms.

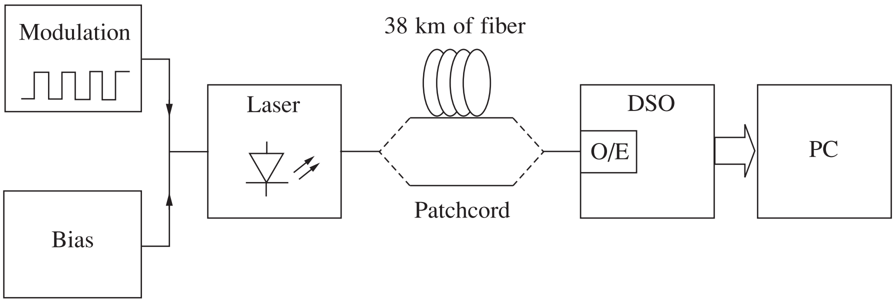

Fig. 4. Measurement setup used in described experiments.

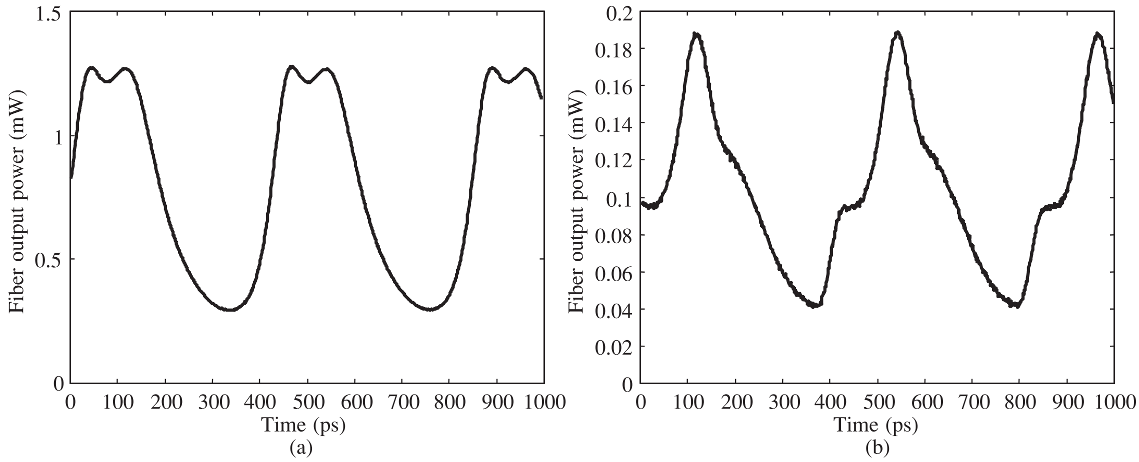

Fig. 5. Example of the measured: laser output (a) and fiber output (b) waveforms.

The described fitting procedure may be arranged as four-dimensional minimisation of error between calculated and measured fiber output waveforms with the use of some standard optimisation method. However, to avoid potential problems associated with multidimentional optimisation and to get better insight into the procedure, in the proposed solution, the fitting is divided into two 2D pieces. The chirp parameters area is uniformly sliced (discretised) in both directions taking reasonable range of parameters and slicing steps. Next, for all pairs of chirp parameters, the calculated fiber output waveform is fitted to the measured one by finding the best values of magnitude scaling and time-domain shift of calculated waveform, using a standard optimisation procedure. The fitting accuracy, defined as inverse of root-mean-square difference between waveforms, is associated with all pairs of chirp parameters. When the obtained dependence of fitting accuracy versus chirp parameters has evident, single maximum, the chirp parameters corresponding to best fitting between measured and calculated fiber output may be regarded as close to its true values.

Practical realization of the chirp parameters estimation is illustrated in Figs. 5–7. The PT3563 laser by Photon was used in the test. Figure 5 shows an example of the measured laser output waveform and resulting fiber output waveform. It may be noticed that fiber output signal shape is noticeably modified (distorted) due to fiber dispersion and laser chirping. Taking laser output signal and chirping model described in Eq. (1), the fiber output was calculated for different values of chirp parameters. The agreement between calculated and measured fiber output (i.e., fitting accuracy) is plotted in Fig. 6 for varying chirp parameters values.

The parameters taken as arguments in Fig. 6 are defined accordingly to some modification of Eq. (1)

$$\Delta\nu(t) = k_{TR}\frac{d}{dt}[\ln(P_L(t))] + k_{AD}P_L(t), \tag{7}$$

in which transient and adiabatic chirps are described by mutually independent, single parameters.

The best fitting between measured and calculated fiber output waveform occurs for k_{TR} = 0.19 and k_{AD} =

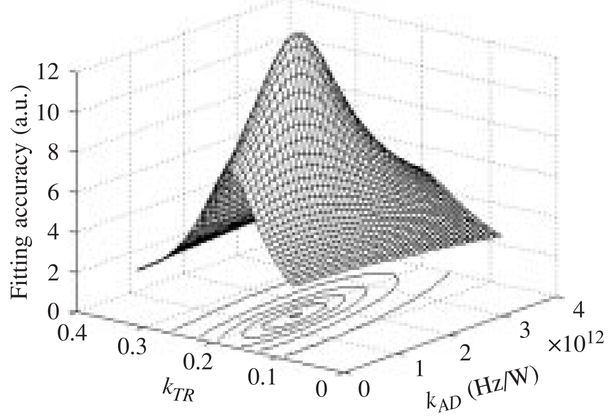

Fig. 6. Fitting accuracy *vs*. chirp parameters.

1.5×10^{12} Hz/W (what corresponds to α = 2.4 and κ = 7.9×10^{12} Hz/W). One period of fiber output waveform, calculated using these values, is shown in Fig. 7, together with the measured waveform and the difference between calculated and measured ones. The evident, single maximum in fitting accuracy (Fig. 6) and very good agreement between fitted and measured fiber output waveforms (Fig. 7) verify the correctness of obtained chirp parameters.

The procedure was also performed for two other 1.55 µm DFB lasers and similar observations were made. Laser types, basic characteristics and obtained chirp parameters values are summarised in Table 1.

Table 1. Basic characteristics of measured lasers and obtained chirp parameters.

Laser type, vendor	Threshold current, nominal power	A	κ
PT3563 photon	9.5 mA 1.5 mW	2.4	7.9×10^{12} Hz/W
C15D lasermate	11.5 mA 1.5 mW	3.15	4.8×10^{12} Hz/W
DFBLD-15-05 AOC	17 mA 1 mW	9.1	10.5×10^{12} Hz/W

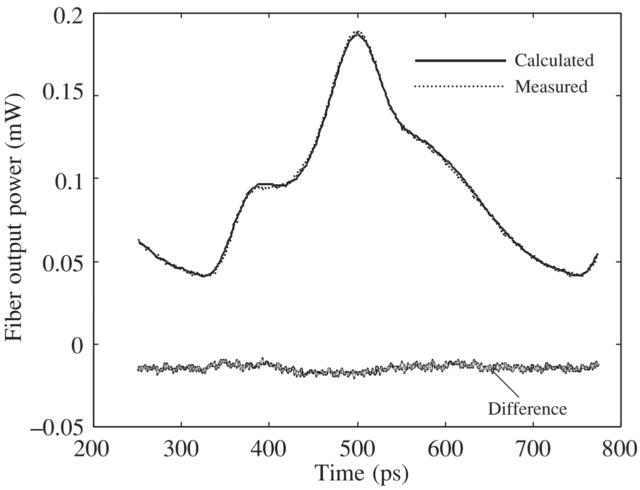

Fig. 7. Comparison of measured and fitted waveforms.

It should be pointed out that in the above measurements, the laser output waveform was not intentionally trimmed to any desired shape. The 2.4-GHz clock generator was used as a signal source. The resulting laser output was influenced by driving electronic characteristics, parasitic capacitances and inductances of laser connections and laser (nonlinear) dynamic characteristics. To investigate the potential impact of the laser output waveform shape on the obtained chirp parameters estimation, the measurements and fitting procedure were repeated for various waveforms. Some examples are shown in Fig. 8. In general, no evident importance of the laser output waveform shape was observed. In all cases, when the fiber output was significantly different from a laser output waveform (i.e., chirping was manifested in a signal distortion), the obtained chirp parameters were similar and good agreement between the calculated and measured fiber output was obtained in all cases.

Spreading of chirp parameters obtained in some tens of different measurement - fitting cycles was about ±3% for k_{TR} and about ±15% for k_{AD}. Less precision of adiabatic chirp parameter estimation is relevant to the fact that in case of high-speed modulation this chirp component is dominated by transient component and so is less pronounced in time-domain signal distortion. Thus, any measurement impairments have relatively larger impact on adiabatic chirp estimation accuracy.

Although the principle of performed measurements is quite simple, some practical problems should be pointed out. One of the important factors is the oscilloscope bandwidth. The described measurements were made using the oscilloscope with 30 GHz bandwidth plug-in. Some measured waveforms (both laser output and fiber output ones) were software filtered by second order low-pass filters, to investigate the impact of bandwidth limitation on chirp parameters estimation. For 10 GHz bandwidth limitation, the obtained chirp parameters were quite close to that obtained from full bandwidth measurements, although the differences between the measured and fitted fiber output waveforms were more pronounced. For bandwidth limited to 5 GHz, the obtained chirp parameters differ from the obtained from full bandwidth measurements in a range of ±10% for transient chirp, and ±30% for adiabatic one, with no systematic tendency. The significant mismatch between the measured and fitted waveforms was observed and fitting accuracy versus chirp parameters plots (similar to this from Fig. 6) had less evident maximum.

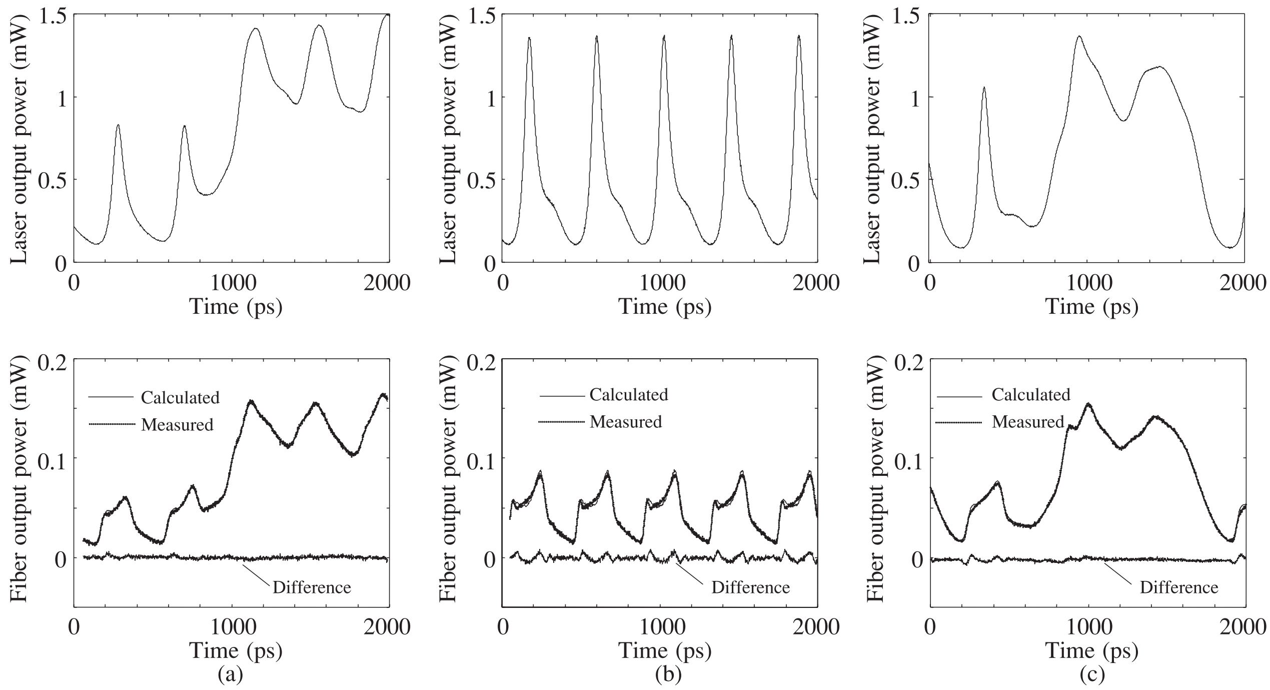

Fig. 8. Measured and fitted waveforms for different laser driving. Plots (a) obtained with laser PT3563, (b) and (c) with C15D.

The oscilloscope DC offset, that may be noticeable with respect to an attenuated fiber output waveform should be carefully eliminated using the scope calibration utilities or by subtracting measured baseline from measured waveforms.

The other important point is frequency stability of laser modulating signal. Because of large propagation delay introduced by the fiber, the signal frequency wander is converted to horizontal wander of measured fiber output waveform observed on the scope. To reduce the oscilloscope noise, measurements should be carried out in averaging mode, so they last some seconds or even tens of second. In this time interval, the wander should be not greater that a few picoseconds. In the presented experiments, commercially available integrated clock synthesising circuit designed for use in synchronous digital hierarchy equipment was successfully used.

Another reason of wandering of the observed fiber output waveform is thermally induced wander of laser center wavelength that, via fiber dispersion, affects the propagation delay. To avoid this wander, the laser and the driving electronics were putted into the box screening them from any air blows and measurements were done after the thermal equilibrium was reached.

To give an example of the impact of measurement impairments, the chirp parameters estimation was repeated using the laser output waveform the same as shown in Fig. 5(a). However, this time, the scope plug-in DC offset (being about 10 μW) was not eliminated and noticeable wander of the fiber output waveform caused by laser temperature fluctuations was observed during measurement. The fitting accuracy versus chirp parameters plot, analogous to that from Fig. 6, is shown in Fig. 9. It may be noticed that the plot maximum is about three times less evident, but estimated laser chirp parameters are very close to that obtained from Fig. 6. This experiment, similarly as the tests with a measurement bandwidth reduction suggests that moderate measurement impairments do not have significant impact on the obtained chirp parameters estimations, although they reduce the waveforms fitting accuracy.

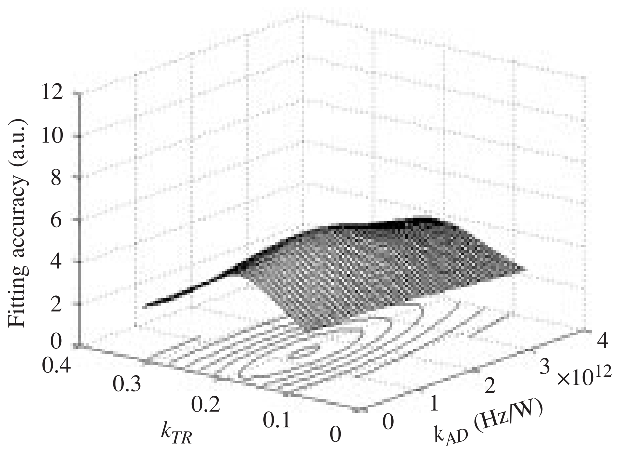

Fig. 9. Fitting accuracy *vs*. chirp parameters obtained for less precise measurements.

5. Conclusions

The presented experiments show that the transient and adiabatic chirp parameters of 1.55 μm DFB laser may be determined using simple method based on time-domain measurements of the distortion of high-speed modulated laser output power transmitted through the dispersive fiber. The measurements do not need any dedicated equipment, so they may be undertaken in any laboratory oriented on a high-speed fiber transmission.

As it was shown, the laser may be simply modulated by a few GHz periodic waveforms. Because there are no particular demands on its shape, the sinusoidal or digital signal generator may be used for laser modulation. However, the frequency stability is crucial.

The chirp parameters estimation is based on signal distortions caused by interaction of a laser chirp with fiber dispersion. Thus, when the good agreement between fitted and measured fiber output waveforms is reached, the taken simple laser chirp and fiber dispersion models may be considered as adequate for the problems concerned with time-domain signal distortions, as for example data eye pattern distortion in real transmission circumstances.

Similar measurements may be undertaken for 1.3 μm single-frequency lasers using fiber having significant chromatic dispersion in this region, such dispersion shifted fiber or dispersion compensating fiber.

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