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Phase and amplitude measurements for high bandwidth optical signals

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ABSTRACT

In this paper a novel technique for obtaining the amplitude and phase of optical pulses with time extents as short as tens of ps is presented. The method which is based on the transport-of-intensity equation only requires, for a practical realization, of passive fiber optic devices. It employs as the main component a dispersive element with a known second order dispersion coefficient. Two different setup implementations are considered, for which simulations are carried out in order to test the method performance taking into account both, realizable models of the involved devices and typical pulses found in optical transmission systems. The characterization of optical pulses affected by dispersion and nonlinear effects, such as self-phase modulation, is used to evaluate the performance of the method and show the practical feasibility of the future implementation.

1. Introduction

All-optical signal processing techniques have taken the attention of the photonics and optical communications scientific community because of its potential advantages regarding aspects such as high processing bandwidth and immunity to electromagnetic interference [1]. The use of passive optical devices translates into simpler and more economic systems than the active optoelectronic counterpart, and obviously but worth mentioning, there is no energy consumption in the process. In recent years, many optical devices have been proposed for switching, filtering and coding signals typically found in optical communication and microwave-photonics scenarios [2,3].

In fiber optic applications, there is much interest in the characterization of optical pulses since the deployment of high bit rate transmission systems which use coherent detection methods that require to estimate the phase value in the demodulation process, e.g. optical pulses present in advanced modulation formats such as QPSK or 16 QAM. Another important use of optical phase recovery methods is in sensing applications, to increase the sensitivity and range of operation fiber optic sensors.

During the 90's, several methods have been proposed to measure the phase of an ultrashort optical pulse and some of them were even converted into commercial devices (Chilla y Martínez [4], Kane y Trebino [5], O'Shea y Trebino [6], Iaconis y Walmsley [7]). Along this development process, also emerged techniques that due to the procedure and/or the technology used for their implementation, they are only capable of measuring the amplitude and phase of pulses with durations in the order of picoseconds. In 1993 it was presented a method called chronocyclic tomography [8] which determines the phase of a pulse from the reconstruction of its associated Wigner Distribution Function (WDF) employing tomographic measurements of the spectrum. In the year 2003, from the base of the latter technique, Dorrer and Kang [9] presented a method which allows to obtain the phase from spectrum measurements of the pulse after being passed through a phase modulator in the temporal domain. That same year, Alieva et al. [10,11], introduced a way to reconstruct the amplitude and the phase of a signal, utilizing measurements of the squared modulus of the fractional Fourier transform with close fractional orders.

In this paper, we present a technique for pulse characterization based on the transport-of-intensity equation and propose a scheme for its photonic implementation which uses only passive fiber optic devices.

2. Signal recovery method

The method here presented is derived from the relationship between the first order WDF moment of a given signal and the

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instantaneous frequency $\nu(t)$ or, equivalently, the first order derivative of the signal phase. This relationship can be written as

$$\int_{-\infty}^{+\infty} \omega W_u(t,\omega)d\omega = \frac{\partial\varphi(t)}{\partial t}|u(t)|^2, \tag{1}$$

being $W_u(t,\omega)$ the WDF associated to a signal $u(t) = |u(t)|\exp(j\varphi(t))$ which can be alternatively defined as

$$W_u(t,\omega) = \int_{-\infty}^{+\infty} u(t+\tau/2)u^*(t-\tau/2)e^{-j\omega\tau}d\tau = \frac{1}{2\pi}\int_{-\infty}^{+\infty} U(\omega+\omega'/2)U^*(\omega-\omega'/2)e^{-j\omega' t}d\omega', \tag{2}$$

where $U(\omega)$ means the Fourier transform of $u(t)$. On the other hand, the WDF associated to a signal $u_f(t)$ whose spectral phase has been quadratically modulated as $U_f(\omega) = U(\omega)\exp(-j\Phi_2\omega^2/2)$ is equal to the WDF associated to the original signal $u(t)$, but affected by a temporal shear. This property is expressed as

$$W_{u_f}(t,\omega) = W_u(t-\Phi_2\omega,\omega), \tag{3}$$

where W_u and W_{u_f} are the WDFs associated to the original and the filtered signals, respectively. The temporal optical power of the modulated signal can be written in terms of its associated WDF as

$$I_{u_f}(t) = |u_f(t)|^2 = \int_{-\infty}^{+\infty} W_{u_f}(t,\omega)d\omega = \int_{-\infty}^{+\infty} W_u(t-\Phi_2\omega,\omega)d\omega. \tag{4}$$

By differentiating (4) with respect to the modulation coefficient it results

$$\frac{\partial I_{u_f}(t)}{\partial\Phi_2} = \int_{-\infty}^{+\infty} \frac{\partial}{\partial\Phi_2} W_u(t-\Phi_2\omega,\omega)d\omega, \tag{5}$$

and by performing the variable change $t' = t - \Phi_2\omega$, Eq. (5) can be rewritten as

$$\frac{\partial I_{u_f}(t)}{\partial\Phi_2} = \int_{-\infty}^{+\infty}\left(\frac{\partial W_u}{\partial t'}\frac{\partial t'}{\partial\Phi_2} + \frac{\partial W_u}{\partial\omega}\frac{\partial\omega}{\partial\Phi_2}\right)d\omega = \int_{-\infty}^{+\infty}\frac{\partial W_u}{\partial t'}(-\omega)d\omega. \tag{6}$$

Now, by taking into account that the variations of the WDF with respect to t and t' are identical, i.e. $\partial W_u/\partial t' = (\partial W_u/\partial t)(\partial t/\partial t') = \partial W_u/\partial t$, Eq. (6) becomes $\partial I_{u_f}(t)/\partial\Phi_2 = -(\partial/\partial t)\int_{-\infty}^{+\infty}\omega W_u(t,\omega)d\omega$. By replacing Eq. (1) into this last expression, it yields

$$\frac{\partial I_{u_f}(t)}{\partial\Phi_2} = -\frac{\partial}{\partial t}\left(I_u(t)\frac{\partial\varphi(t)}{\partial t}\right). \tag{7}$$

Eq. (7), sometimes referred as the temporal transport-of-intensity equation, has been used to measure temporal phase shifts induced by self-phase modulation or cross-phase modulation [12], and is the fundament of the method here presented which can be considered as the temporal domain analogue of an spectral approach proposed by Dorrer et al. [9]. Although Eq. (7) was derived from a WDF property, an approach based directly on the transport-of-intensity equation might also be used to obtain the same expression. There is an important issue regarding the uniqueness of the retrieved phase from the transport-of-intensity equation, that needs to be mentioned. Although the recovered phase is unique under a linear propagation condition, it has been shown that the solution has an ambiguity when there are zeros in the intensity distributions [13].

From Eq. (7) it is possible to recover the phase of a given signal. Nevertheless, in order to obtain a feasible and easily attainable procedure, some approximations should be made. First, the derivative with respect to the modulation coefficient can be replaced by a centered finite difference approximation as

$$\frac{\partial I_{u_f}(t)}{\partial\Phi_2} \cong \frac{I_{u_f}(t)\big|_{\Phi_2} - I_{u_f}(t)\big|_{-\Phi_2}}{2\Phi_2}. \tag{8}$$

The quadratic spectral phase modulation can be produced by transmission of the signal through an optical fiber, being Φ_2 the second order dispersion coefficient at the central angular frequency ω_0, multiplied by the fiber length. This may be understood by analyzing the propagation of a light pulse through a nonlinear dispersive medium under a slow envelope approximation and considering that the nonlinear response is instantaneous, and weak, in order to apply a first-order perturbation theory. This situation, can be modeled employing the nonlinear Schrödinger equation which is shown as Eq. (9).

$$\frac{\partial u}{\partial z} + j\frac{\beta_2}{2}\frac{\partial^2 u}{\partial\tau^2} - \frac{\beta_3}{6}\frac{\partial^3 u}{\partial\tau^3} + \frac{\alpha}{2}u = -j\gamma|u|^2 u \tag{9}$$

being β_2 and β_3 the second and third order dispersion (TOD) coefficients, respectively, α the attenuation coefficient, γ the nonlinear parameter, and $\tau = t - z/v_g = t - \beta_1 z$ the time reference moving with the pulse at group velocity (traveling-wave coordinate system). Eq. (9), under typical conditions of propagation through a short length optical fiber (attenuation term might be discarded since $\alpha z \approx 0$), can be simplified to Eq. (10a) or to its spectral version, Eq. (10b), by neglecting the TOD term due to its usually much smaller value than the second order one ($\beta_3\Delta\omega^3 3 \ll \beta_2\Delta\omega^2$, being $\Delta\omega$ the spectral width of the pulse), and considering a linear regime case when the optical power value is low enough ($\gamma|u|^2 \approx 0$).

$$\frac{\partial u}{\partial z} = -j\frac{\beta_2}{2}\frac{\partial^2 u}{\partial\tau^2} \tag{10a}$$

$$\frac{\partial U}{\partial z} = j\frac{\beta_2}{2}\omega^2 U \tag{10b}$$

Finally, Eq. (10b) or its form after integration, $U(z,\omega) = U(0,\omega)\exp(j\beta_2\omega^2 z/2)$, shows how transmission of the signal $u(t)$ through an optical fiber of length z having second order dispersion coefficient β_2 may be used to achieve the quadratic spectral phase modulation needed to implement Eq. (8), being $\Phi_2 = -\beta_2 z$. Another implementation of such spectral phase modulation is the use of the reflection characteristic of a linearly chirped fiber Bragg grating (LCFBG) with dispersion parameter or group delay slope Φ_2.

In this way, the temporal optical power derivative can be implemented by two temporal detections of the signal, each one affected by the same amount of second order dispersion, but having opposite signs. Taking advantage of this implementation, the optical power $I_u(t)$ can be approximated by the average of the two detections of the dispersed signal as

$$I_u(t) \cong \frac{I_{u_f}(t)\big|_{\Phi_2} + I_{u_f}(t)\big|_{-\Phi_2}}{2}. \tag{11}$$

It is worth noting that Eqs. (8) and (11) are only valid whenever the second order dispersion coefficient Φ_2 remains small. Thus, in order to find the restrictions for Φ_2, lets consider a pulse with temporal and spectral widths Δt and $\Delta\omega$, respectively, being both symmetrical in a first approach. Since Φ_2 is equal to the tangent of the shearing angle of the WDF domain produced by the quadratic spectral phase modulation, it can be easily shown that the second order dispersion coefficient should be much lower than the ratio of the temporal width to the spectral width; i.e.,

$$\Phi_2 \ll \Delta t/\Delta\omega. \tag{12}$$

Fig. 1 shows two different implementations of the system proposed for recovering the amplitude and phase information of a pulse. The schematic diagram of Fig. 1(a) uses two single mode optical fibers (SMF), a standard one and a dispersion compensating

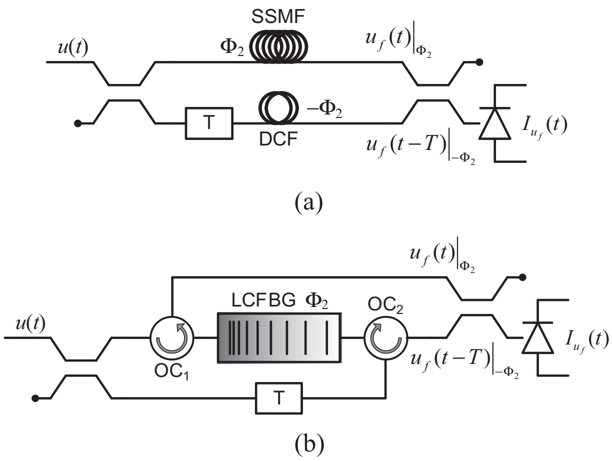

Fig. 1. Schematic diagrams of two different implementations of the phase recovery technique. (a) Based on SMF. (b) Based on LCFBG. SSMF, standard single mode fiber; DCF, dispersion compensating fiber, LCFBG, linearly chirped fiber Bragg grating; OC_1 and OC_2, optical circulators.

fiber (DCF), both having the same amount of second order dispersion. The fibers quadratically modulate the spectral phase of each pulse obtained from the left 50/50 coupler. The lower branch pulse is delayed a certain time T (longer than the pulse width) just to avoid the overlapping of the dispersed pulses on the photodetector after the combination performed by the right coupler. In the other implementation shown in Fig. 1(b), the input pulse $u(t)$ is split into two signals by the left 50/50 coupler. One pulse, after propagation through the left circulator (OC_1) and reflection from the left side of the LCFBG, is again circulated by OC_1 and detected after passing the right 50/50 coupler. The second pulse, after being delayed by a time T and circulated by OC_2, experiments a second order dispersion of opposite sign, since it is reflected from the right side of the LCFBG. Thus, in both implementations, after two consecutive detections, the phase of $u(t)$ can be recovered employing Eqs. (7), (8), and (11). It is worth noting that both implementations of Fig. 1 make use of directional couplers as signal dividers/combiners, so there's a 90° phase shift between the signals after/before each device. Nevertheless, in both implementations, the signals present in the two branches of the system are equally phase shifted 90° so this effect can be disregarded in the analysis.

3. Numerical results

In order to illustrate the performance of the proposed method, it is considered the characterization of three different types of pulses. First, it is presented the characterization of a pulse that has been mainly affected by SPM and by second order chromatic dispersion, employing the device based on a LCFBG that is sketched in Fig. 1(b). To this end, the signal to be recovered $u(t)$ arises from an unchirped Gaussian pulse of initial RMS width $T_0 = 50$ ps when it is transmitted through 20 km of NZ-DS (Non-Zero Dispersion-Shifted) fiber equivalent to $2.6 \times L_{NL}$ and $0.07 \times L_{D2}$, being $L_{NL} = (\gamma P_0)^{-1}$ the nonlinear distance and $L_{D2} = T_0^2|\beta_2|$ the second-order dispersion length. Fig. 2(a) and (b) shows two numerical results comparing the ideal optical power and phase distributions of $u(t)$ with the recovered signals, when two different LCFBGs are employed, both having the same length (3.5 cm) and dispersion parameter ($\Phi_2 = 67.0$ ps^2), but different ripple levels. This value of Φ_2 is approximately twenty times smaller than the temporal width to spectral width ratio, i.e. $\Delta t/\Delta\omega = 146$ ps/(2π17.3 GHz) = 1341 ps^2, fulfilling the condition established by Eq. (12). The temporal and spectral widths are considered to be where 95% of the pulse energy is comprised. In Fig. 2(a) and (b) are displayed the original and the recovered pulses when it is used the corresponding LCFBGs of Fig. 2(c) and (d), respectively. It can be observed that, in both cases, the pulse has been successfully recovered, being the optical power and phase waveforms quite similar to the original ones. Nevertheless, it is necessary to note that the LCFBG having a higher ripple level provides a slightly poorer phase reconstruction. The difference in the ripple level associated with each LCFBG can be observed in the reflectivity and group delay curves shown in Fig. 2(c) and (d), when a raised cosine apodization and no apodization is used, respectively.

As is shown in the Fig. 2(a) and (b), both the recovered optical power and phase have a great resemblance with the original pulse proving the ability of the proposed method and device to measure and characterize optical pulses. Finally, it is important to mention that the detection of the dispersed pulses it was calculated by considering a Signal-to-Noise Ratio SNR = 25 dB, where the noise was supposed to have Gaussian statistics, and the results shown in Fig. 2(a) and (b) were obtained employing an average of $N = 100$ realizations of the detected optical powers.

Next, we analyze how the SNR affects the performance of the proposed system when a single shot detection of the pulse is characterized (no averaging over realizations is performed), and the device based on SMF sketched in Fig. 1(a) is used. In this case the pulse recovered has hyperbolic secant shape, a RMS width $T_0 = 100$ ps and a linear chirp parameter $C = 6$ (linear variation of the optical frequency). Fig. 3 shows the original and the recovered pulses for two SNR values of 15 and 30 dB, in (a) and (b), respectively. It can be observed that the system is able to approximately recover the pulse phase even from a single shot detection when the SNR value is 30 dB. However, when the SNR value present in the detection stage is 15 dB, the device cannot obtain an acceptable phase waveform. This is in accordance with the fact that we are not trying to estimate a discrete value represented by a digital signal, but rather obtain its phase and optical power waveforms. The task of characterizing a pulse inherently requires a high SNR value, i.e. a relatively high signal power since all the noise corrupting the signal is the one introduced by the detection stage, or equivalently needs a mean to reduce the noise variance, e.g. by averaging the detected realizations of the dispersed pulse amplitude for this particular method.

It is worth noting that in the last example, the simulation of the system was performed considering a standard SMF and a DCF, both including dispersion coefficients up to the third order, being the optical fiber sections of the device 4134 m and 267 m long, for the SMF and the DCF, respectively. Nevertheless, the relatively low value of both TOD coefficients verify the approximation $\beta_3\Delta\omega^3 3 \ll \beta_2\Delta\omega^2$, that was taken into account to reach Eqs. (10a) and (10b), and which is needed to obtain the quadratic spectral phase modulation required by the method. Therefore, the implementation of Fig. 1(a) shows a good performance even for regular optical fibers since it tolerates the small amount of TOD that they usually have. Of course, for this type of implementation, the attenuation of both fiber sections needs to be compensated, especially because DCFs generally have a relatively much higher value of attenuation coefficient than standard SMFs.

Now, in order to complete the performance evaluation of the proposed measurement technique and system implementation, we consider the characterization of a more complex pulse shape. In this case the device of Fig. 1(a) is used to recover the phase and optical power of a Gaussian pulse which has undergone the effects of TOD and a residual second order dispersion, e.g. a pulse which has propagated through a long haul optical fiber link with almost perfect second order dispersion compensation. Fig. 4(a) shows the retrieved and original pulses for a SNR value of 40 dB when an averaging of $N = 100$ realizations of the detected optical power is performed. It can be appreciated that the phase jumps

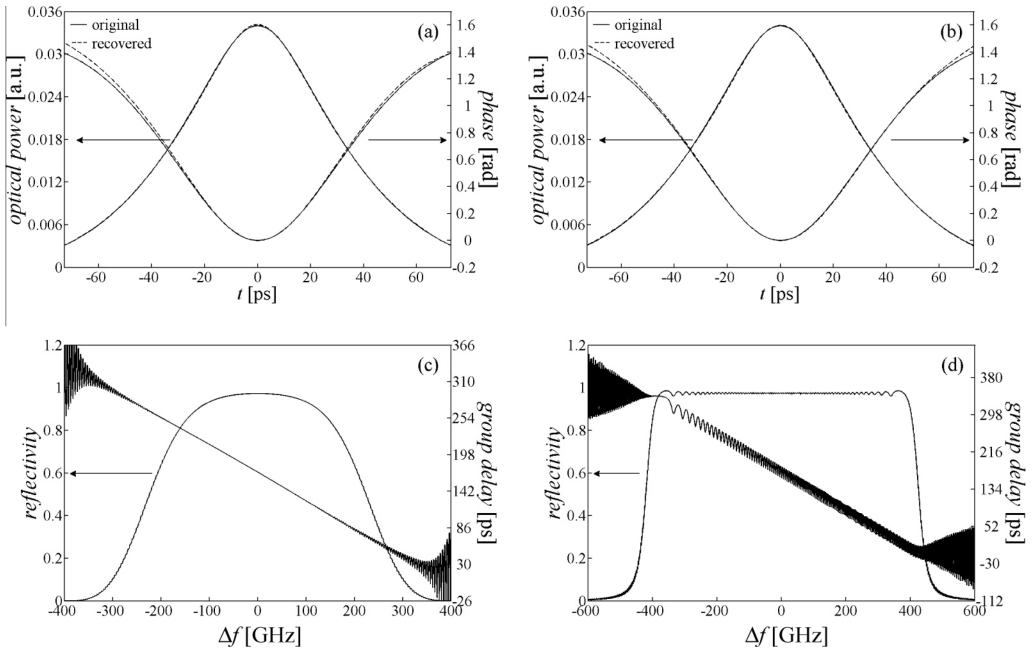

Fig. 2. Recovery of a pulse that has been affected by SPM using the system of Fig. 1(b) and employing two different LCFBGs of 3.5 cm long having the same dispersion parameter $\Phi_2 = 67.0\ \text{ps}^2$. (a) Original and recovered pulse using the LCFBG shown in (c). (b) Original and recovered pulse using the LCFBG shown in (d). Reflectivity and group delay of the LCFBG when (c) has a raised cosine apodization (low ripple level) and (d) has no apodization (high ripple level).

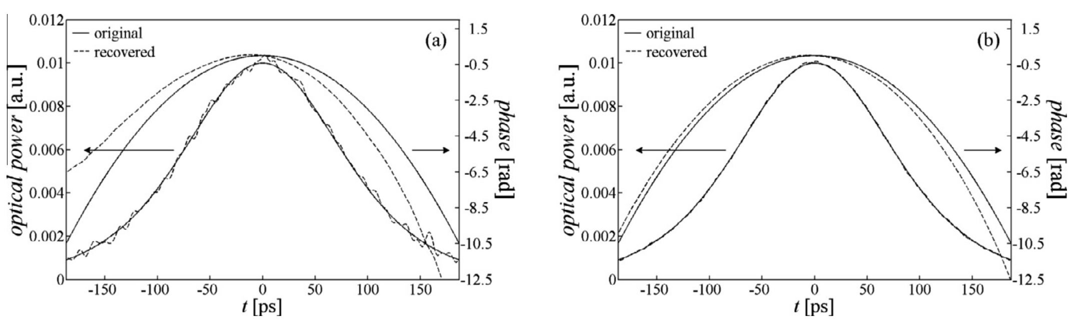

Fig. 3. Effect of the SNR value over the performance of the system in single shot detection mode. Original and recovered pulse when (a) SNR = 15 dB and (b) SNR = 30 dB.

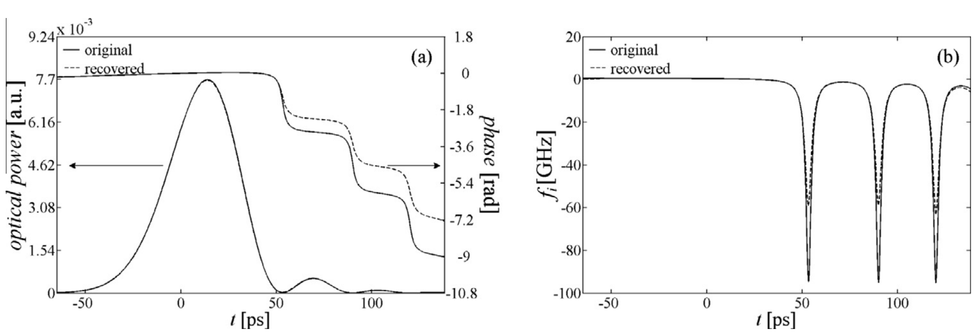

Fig. 4. Recovery of a pulse that has been affected by TOD using the system of Fig. 1(a) with SNR = 40 dB and an averaging of $N = 100$ realizations. (a) Optical power and phase of the original and the recovered pulse. (b) Original and recovered instantaneous frequency.

inherent to this kind of pulse cannot be accurately recovered, even with such high SNR value and variance reduction processing. This pitfall of the method implementation may be understood by a more thorough analysis of the recovery technique. The first step of the phase retrieving process is to obtain the instantaneous angular frequency $\omega_i = \partial\varphi/\partial t$ of the pulse as shown in Eq. (13), which corresponds to Eq. (7) rewritten in a more adequately form.

$$\omega_i(t) = -\frac{1}{I_u(t)} \int \frac{\partial I_{u_f}(t)}{\partial \Phi_2} dt. \tag{13}$$

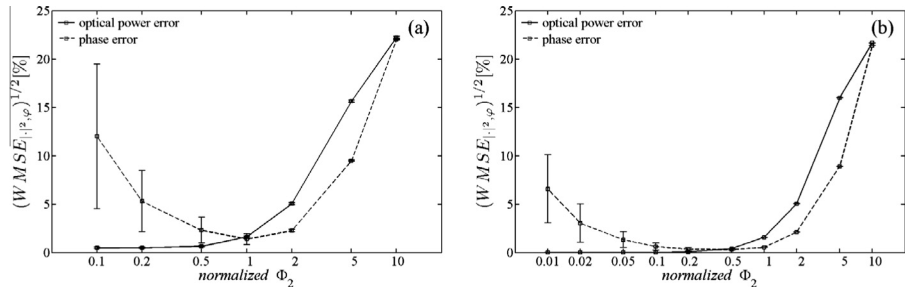

Fig. 5. Average WMSE and its standard deviation for the same pulse shape of Fig. 2(a). WMSE of the optical power and the phase for (a) SNR = 15 dB and (b) SNR = 40 dB. The phase error is displayed as a percentage of the whole phase excursion in the temporal interval considered (95% of the pulse energy).

As has been stated in the previous section, the derivative of the optical power of the pulse, after its spectral phase has been quadratically modulated, is approximated by the centered finite difference shown as Eq. (8). The particular kind of pulse we are considering has phase jumps, or equivalently instantaneous frequency peaks, as it can be observed in Fig. 4(b) where the original and the recovered instantaneous frequency, $f_i = \omega_i(2\pi)$, of the pulse is shown. The maximum values of the f_i peaks are not accurately retrieved since they appear in a very short range of time where the optical power is almost null. This situation would be more notorious for the case of a pulse affected only by TOD (without residual second order dispersion) since its instantaneous frequency peaks would ideally tend to be Dirac delta functions. Therefore, the instantaneous frequency (or the phase) of such kind of pulses is very difficult to estimate from the integration of a derivative approximation consisting of the subtraction of two optical power detections of light pulses with a slow envelope representation. In addition, the recovery of a phase with transitions in the time interval where the optical power of the pulse has a low value, is also affected by two issues regarding the implementation which cannot be overlooked: the noise introduced in the detection stage and the temporal resolution of the sampling stage, that should not be larger than the duration of the phase transition.

4. Choosing a proper value of Φ_2

The value of Φ_2 which determines both optical powers of the dispersed pulses, $I_{u_f}(t)\big|_{\Phi_2}$ and $I_{u_f}(t)\big|_{-\Phi_2}$ (see Eqs. (8) and (11)), should be carefully chosen. If it is too small, the optical power of the recovered pulse is excellently approximated by the average but the derivative in Eq. (8) becomes strongly unstable due to the amplification effect of the detection error which is inherent to the method. This situation is avoided by choosing a value of Φ_2 large enough. However, in this case the optical power is not truly represented by the average in Eq. (11), and Eq. (8), although becoming stable, would not provide a good derivative approximation. In order to define a proper value of the dispersion parameter and to establish a valid range of the method, the deviations of both, the recovered optical power and phase waveforms with regard to the original pulse, are analyzed when different values of Φ_2 are selected. For this purpose, it is calculated the Weighted Mean Squared Error (WMSE) selecting a temporal range where 95% of the pulse energy is comprised and employing the optical power as the weighting function. In order to isolate the impact of the dispersion parameter on the recovery procedure, it is employed the system shown in Fig. 1(a). Fig. 5 shows the average WMSE and its standard deviation of the optical power and the phase. The waveform to be recovered is the same pulse affected by SPM and chromatic dispersion which was used in Fig. 2. Now, the abscissa is normalized to the dispersion value $0.1\Delta t/\Delta\omega$ (the tenth part of the pulse's temporal to spectral width ratio). These results were obtained considering a detection noise with Gaussian statistics, SNR of 15 dB in (a), and SNR = 40 dB in (b), for the same given system conditions, and a temporal optical power average over $N = 100$ realizations. It should be selected a value of Φ_2 which provides a compromise between a low value of the WMSE for both, the optical power and the phase. Therefore, for a given pulse having temporal and spectral width of Δt and $\Delta\omega$, respectively, this condition establishes an interval for Φ_2 where the optical power and phase are reconstructed with an error lower than a specified limit value. Fig. 5(a) shows that for the normalized Φ_2 approximately between 0.5 and 2 (it is equivalent to Φ_2 between 0.05 $\Delta t/\Delta\omega$ and 0.2 $\Delta t/\Delta\omega$), permits to obtain an average WMSE lower than 5% in the phase and optical power measurements, for SNR = 15 dB. Similarly, when the SNR is 40 dB from Fig. 5(b), the measured phase presents an average WMSE lower than 5% when the normalized Φ_2 is between approximately, 0.02 and 4, while for the optical power, the normalized Φ_2 has to be lower than 2. Clearly, the performance gets increased for higher SNR values as can be appreciated by comparing Fig. 5(a) and (b).

5. Conclusions

The proposed system is based in the simple, but powerful, transport-of-intensity equation and can be applied to any shape of pulses. However, the approximations performed in order to obtain a feasible and practical implementation, with real devices, limit the operation range. One of these restrictions is given by the bandwidth of the photoreceiver which limits the shortest duration of the input pulses. For instance, employing a photodetector with a bandwidth of 20 GHz would enable the characterization of pulses with a duration not lower than approximately 50 ps. Another important parameter to be taken into account in the design of the system is the noise present in the detection process. If the system presents a SNR value lower than approximately 15 dB, the numerical simulations realized on many types of pulses confirm that the performance is considerably reduced and the optical power and phase measurements have an unwanted large variance. This situation can be understood by considering that the approximation of the derivative, Eq. (8), becomes unstable due to the error amplification caused by the present noise. This limit is also dependant on the pulse shape and might be higher for complex waveforms. When the SNR values are between the range of approximately 15–35 dB, the system performs very well when the variance of the detection noise is reduced by averaging. Of course, for the latter kind of processing, a repetitive type of pulse is needed. In the best case scenario of the system operating with a high enough SNR value, i.e. approximately higher than 35 dB, the proposed implementation may even be used in a single shot mode. Nevertheless, care should be taken when the input power is increased in order to obtain a larger SNR value. If the optical power of the input pulse rises above the limit for which the nonlinear effects of the optical fiber cannot be neglected the principle of operation of the device would no longer be valid and its performance shall worsen.

Finally, it is worth mentioning that the main advantage of the proposed technique lies on the possibility to employ simple and economic passive optical devices together with a sampling oscilloscope (including a photodetector with the previously cited characteristics) to retrieve the phase and optical power of large bandwidth pulses in the ps-range, such as those observed in modern optical communication systems.

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