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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

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

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