Optics Communications 338 (2015) 292–299

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Monitoring the dominance of higher-order chromatic dispersion with spectral interferometry using the stationary phase point method

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ARTICLE INFO

Article history:
Received 22 July 2014
Received in revised form
30 September 2014
Accepted 21 October 2014
Available online 30 October 2014

Keywords:
Stationary phase point method
Spectral interferometry
Chromatic dispersion
Photonic bandgap fiber
Prism pair

ABSTRACT

Simulations were performed in order to investigate whether the stationary phase point method can be used to estimate the dominance of higher-order dispersion of the optical element under study. It was shown that different higher-order dispersion terms may result in the appearance of more than one stationary phase point on the interferogram in contrast to common glasses having group-delay dispersion as the highest decisive term in their spectral phase. The results obtained by simulations were demonstrated experimentally with spectral interferometric measurements conducted on a photonic bandgap fiber sample and a prism pair. We concluded that from the shape, movement and number of the stationary phase points it is generally possible to predict which dispersion terms are the most significant, however, in some cases the retrieval of the coefficients is also necessary in order to rule out any ambiguity. The method can offer a dispersion monitoring possibility which is useful in quality testing of specialty fibers and when adjusting stretcher-compressor systems, for example.

1. Introduction

Nowadays there are countless applications relying on optical fibers which require precise control of certain characteristics, such as dispersion, birefringence or nonlinear behavior. Bragg-type [1] and photonic crystal fibers [2–5] have received considerable attention owing to their unique attributes, which can be tailored by the proper design of their geometrical structure. To date, a considerable amount of effort has been devoted to decrease the second-order, so-called group-delay dispersion (GDD) and the third-order dispersion (TOD) of the fibers, which are responsible for pulse broadening and post- or pre-pulses, respectively. Doing so, the fourth- (FOD) and higher-order dispersion become significant unlike in common materials which do not exhibit such dispersion characteristics.

A similar effect is observable in high power laser systems relying on chirped pulse amplification (CPA) [6]. Numerous solutions have been proposed to eliminate the GDD and the higher-order dispersion terms of the stretcher and the amplifier stage with the compressor in order to obtain nearly transform-limited pulses at the output of a CPA laser [7–14]. Nonetheless, reducing the GDD and the TOD generates uncompensated FOD in the system [13,14] which might be of concern in applications requiring pulses with ultrahigh contrast. All in all, it can be concluded that reduction of the lower-order dispersion results in pronounced contribution of the higher-order dispersion which limits the performance of the fiber in pulse propagation or the achievable peak power in a CPA laser.

Retrieval of the pulse duration is of great prominence, however, when optimizing laser systems retrieval of the spectral phase is even more important as it shows the residual dispersion of the pulse. As certain pulse distortions can be associated with given dispersion terms, monitoring and precise measurement of the higher-order dispersion is essential. Numerous pulse diagnostic schemes have been invented, which can be divided into self-referencing and non-referencing schemes. The oldest self-referencing method the interferometric autocorrelation (IAC) accompanied by the pulse spectrum can be used to retrieve the pulse shape and the spectral phase, as various chirps produce distinctive patterns. Despite its benefits, the method contains an ambiguity in the sign of the chirp and moreover the accuracy of the chirp measurement is not very high [15]. Frequency-resolved optical gating (FROG) is another autocorrelation-type measurement possibility which has several implementations, such as polarization gate (PG), self-diffraction (SD), transient grating (TG), second- (SHG) or third-harmonic generation (THG) FROG [16]. PG FROG is a complete and unambiguous pulse characterization technique although requires high-quality polarizers thus it is very expensive.

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http://dx.doi.org/10.1016/j.optcom.2014.10.047
0030-4018/

SD FROG, a bit cheaper solution which involves third-order nonlinearity as well, is more sensitive to even-order temporal-phase distortions, but less to the odd-orders. TG FROG requires no polarizers and is more sensitive compared to the previous ones; however its need for three beams can be disadvantageous. SHG FROG involves only second-order nonlinearity, thus has a stronger signal. It is slightly less sensitive than IAC and has an ambiguity in the direction of time as well. THG FROG on the other hand removes the direction of time ambiguity but in turn is less sensitive than the SHG version. The method is more sensitive than the other previously mentioned third-order FROG methods, but it contains relative phase ambiguities unlike them. Another problem arises in the case of perfectly linearly chirped Gaussian pulses as the sign of the chirp parameter cannot be determined with THG FROG. Yet another technique, based on the modification of IAC, modified spectrum auto-interferometric correlation (MOSAIC) was developed for real-time dispersion control [17–20]. MOSAIC is very sensitive to chirp, even for lower values, as opposed to IAC, and produces distinctive patterns for different orders. It offers detection of the presence of chirp thus a real-time optimization possibility. Unfortunately, the same signal can be generated by several combinations of various order chirps and in addition to time direction ambiguity; accordingly, the method can be used only for qualitative determination. However, if not only the peak amplitude of the envelope of the interference minima of the MOSAIC signals are used, but also the temporal shape is studied quantitative information regarding the chirp can be required. The exact values of given terms can be obtained by iterative processes [18]. Different approaches were developed to reduce calculation time and remove uncertainties, such as envelope (E)-MOSAIC algorithm which, combined with measurement of differential fringe phase (DFP) using software control (LabVIEW) control yields a sign-sensitive phase retrieval technique [20]. Considering that in most cases a direct feedback is necessary, avoiding complicated, time-consuming data collecting methods would be favorable. Interferometric methods in general require the collection of less data than spectrographic methods, and thanks to their direct inversion algorithms they enable rapid pulse reconstruction. Spectral phase interferometry for direct electric field reconstruction (SPIDER) for instance is a promising candidate. Using LabVIEW adds to the relative easy implementation of the method [21]. A detailed comparison of IAC, two types of SPIDER and interferometric (I) FROG conducted by Stibenz et al. [22] revealed some considerations. It was concluded that IAC is of great service to verify other techniques, SPIDER becomes less reliable with increasing complexity of the pulses to be measured, a spatially encoded arrangement (SEA) of SPIDER gathers a large number of data thus it is less suitable for high data acquisition rates, but advantageous for complex, low energy pulses, and IFROG uses iterations to reconstruct the pulse and the phase, which need further improvements. In terms of simplicity cost one might consider using linear methods which do not require expensive high quality nonlinear crystals or 2D detection schemes. Spectral interferometry is a widely used extremely sensitive linear technique for dispersion characterization of different optical elements which does not necessarily require a laser and works fine with white light as well. For spectral phase retrieval there are more evaluation methods at our disposal. The precision of the Fourier-transform evaluation method in measuring higher-order dispersion is already demonstrated [23,24], however if dispersion retrieval in a wide wavelength range is of interest, thus a lower resolution spectrometer is used, the method becomes inaccurate. On the other hand, the so-called stationary phase point (SPP) method [25–29], also known as equalization wavelength, is one of the most common evaluation methods, the applicability of which has already been demonstrated in measuring the dispersion of various optical elements, including fibers [23,24,30–32]. The SPP method is advantageous as regardless of the value of the dispersion and the resolution of the spectrometer the positions of the SPPs can be precisely determined [28]. Up until now this method was mainly used only in the case of optical elements and fibers where the GDD was the decisive dispersion term, however, recent studies show that even fifth-order dispersion (QOD) has significance when the GDD is reduced and the TOD becomes dominant [23,24]. In that case two SPPs were detected at certain delays, and the group delay curve was determined from the positions of both SPPs. Accordingly, it is worth investigating the possibility of forming more than two SPPs and whether their number suggest which is the highest decisive term in the spectral phase of the optical element or system under study. Moreover, a two-dimensional dispersion monitoring possibility in a pulse stretcher-compressor system has already been proposed employing the SPP method proving its adequacy for such purposes, however, only up to third-order dispersion [33]. It would be beneficial to investigate whether a cheaper implementation relying on a low resolution spectrometer using the SPP method can be used for the same purpose.

In this work we present a detailed study regarding the relation between the SPPs and the higher-order dispersion terms. We investigate the possibility of monitoring the dominance of the dispersion orders by studying the shape, movement and number of SPPs appearing on spectral interferograms. The effects of given dispersion terms up to the fifth order on the spectral interferogram are demonstrated using simulations. Measurements were performed on a Bragg-type solid-core photonic bandgap (PBG) fiber sample and a prism pair to demonstrate the usefulness of the method.

2. Theory

Spectral interferometry is a common tool in dispersion measurement and spectral phase retrieval of various optical elements. The technique utilizes a two-beam interferometer, usually a Michelson or Mach–Zehnder type, illuminated with a broadband light source, for instance an ultrashort pulse laser or a tungsten halogen lamp. The optical element or system, the dispersion of which is tested, is placed in one arm of the interferometer, while the other arm provides a reference and has adjustable path length. As the two beams from the sample and the reference arms interfere, fringes can be observed at certain arm length differences. The fringes can be studied utilizing a spectrometer placed at the output of the interferometer. The frequency-dependent intensity distribution $I(\omega)$ of the interference pattern can be written as

$$I(\omega) = I_s(\omega) + I_r(\omega) + 2\sqrt{I_s(\omega)I_r(\omega)}\cos(\Phi(\omega)), \tag{1}$$

where I_s and I_r denote the spectral intensities of the sample and the reference beams, respectively, and Φ is the spectral phase difference between the arms

$$\Phi(\omega) = \varphi(\omega) + \frac{\omega}{c}(l_s - l_r) = \varphi(\omega) + \omega\tau. \tag{2}$$

In Eq. (2) $\varphi(\omega)$ stands for the spectral phase of the sample, l_s and l_r are the path lengths of the light beams in the sample and the reference arms in air, respectively. We presumed that the refractive index of the air equals to 1, c denotes the velocity of light in vacuum and τ is the time delay arising from the arm length difference.

As an ultrashort laser pulse travels through a dispersive optical element or system, its temporal intensity profile undergoes a change that is only determined by the spectral phase introduced by the elements, assuming that the variation in the amplitude of