Optics Communications 416 (2018) 160–165

Contents lists available at ScienceDirect

Optics Communications

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

Gaussian temporal modulation for the behavior of multi-sinc Schell-model pulses in dispersive media

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ARTICLE INFO

Keywords:
Coherence
Pulse
Convolution operation
Multi-sinc Schell-model temporal correlation

ABSTRACT

A new class of pulse source with correlation being modeled by the convolution operation of two legitimate temporal correlation function is proposed. Particularly, analytical formulas for the Gaussian temporally modulated multi-sinc Schell-model (MSSM) pulses generated by such pulse source propagating in dispersive media are derived. It is demonstrated that the average intensity of MSSM pulses on propagation are reshaped from flat profile or a train to a distribution with a Gaussian temporal envelope by adjusting the initial correlation width of the Gaussian pulse. The effects of the Gaussian temporal modulation on the temporal degree of coherence of the MSSM pulse are also analyzed. The results presented here show the potential of coherence modulation for pulse shaping and pulsed laser material processing.

1. Introduction

It is well known in statistic optics that the far field spectral density is proportional to the spatial Fourier transform of the source degree of coherence, one of the famous reciprocity relations known to be of Fourier-type law [1]. According to the law, various new model sources with nonconventional correlation function have been developed in the spatial domain. Many extraordinary properties are induced by the special correlation form in the far fields, Such as self-focusing and lateral self-shifting of the intensity maxima of the beam with non-uniformly correlation function [2,3], self-splitting of the beam with Hermite–Gaussian correlated function or cosine Gaussian correlation with rectangular symmetry [4,5], and self-shaping of the beam with multi-Gaussian Schell-model correlation function or sinc-Schell correlation [6,7]. These unique features of the special correlated partially coherent beams indicate that such beams carry potential for practical application involving lasing detection, optical shaping, and atmosphere optical communications. In addition, apart from the classic weighted summation of the coherent modes, more general linear combinations including difference, products and powers of two degrees of coherence have been shown to lead to novel random sources and fields radiated by them [8–11]. Recently, convolution of two degrees of coherence is confirmed to represent a novel legitimate degree of coherence [12]. And convolution operation being a new method for intensity modulation of the produced far fields is illustrated [13].

The studies of the influence of coherence properties on the beams upon propagation has not only been confined to statistically stationary light source, but also been extended for the stochastic optical pulses representing a wide class of partially coherent non-stationary fields [14–24]. The basic model characterizing partially coherent light pulses in temporal domain is the Gaussian Schell-model pulse, of which the evolution of the pulse width on propagation in dispersive medium greatly depends on the width of the temporal degree of coherence [14,15]. Apart from the classic model, some new partially coherent pulsed models with non-Gaussian Schell-model temporal correlations are introduced, which are shown to lead to novel intensity profiles on propagation in dispersive media. Pulses with non-uniform correlation distribution are shown to produce a self-focusing and temporal shift of the intensity maximum [19], Pulses with sinc Schell-model temporal correlation and Multi-Gaussian Schell-model temporal correlation acquire flat intensity profiles with controllable duration and edge sharpness [20]. Moreover, it is shown that a linear superposition of several Multi-Gaussian-correlated pulse ensembles can realize the pulse-position modulation [21]. The method for generating partially coherent light pulses experimentally has been demonstrated in [24].

In this paper, we will show that in the temporal domain convolution of the degrees of coherence can be used for modulation of pulse average intensity and degrees of coherence. The source model for the source temporal degree of coherence being convolution of Gaussian Schell-model temporal correlation function and MSSM temporal correlation

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https://doi.org/10.1016/j.optcom.2018.01.062
Received 13 December 2017; Received in revised form 29 January 2018; Accepted 30 January 2018

function are introduced. How the unique correlation properties affect the propagation characteristics of the pulse ensembles generated by pulse source in dispersive media are analyzed in detail.

2. Source model

The mutual coherence function characterizing the second-order temporal correlation properties of the ensemble of random, statistically stationary pulses is given by [1]

$$\Gamma^0\left(t_1,t_2\right)=\sqrt{I^0\left(t_1\right)}\sqrt{I^0\left(t_2\right)}\gamma^0\left(t_1,t_2\right), \tag{1}$$

where $I^0(t)$ is the average intensity of the partially coherence pulse at time $t, \gamma^0\left(t_1,t_2\right)$ denotes the degree of coherence of the pulse.

As has been shown for the correlation functions in the spatial domain, the sufficient condition for the temporal correlation function to be physically realizable is that it can be represented in the form

$$\Gamma^{(0)}\left(t_1,t_2\right)=\int p(v)\, H_0^*\left(t_1,v\right) H_0\left(t_2,v\right) dv, \tag{2}$$

where $H(t,v)$ is an arbitrary kernel and the weighting function $p(v)$ is a non-negative, Fourier-transformable function. For Schell-Model (SM) pulsed beams, H_0 takes on the form:

$$H_0(t,v)=\exp\left(-\frac{t^2}{4\sigma_{t0}^2}\right)\exp(-ivt), \tag{3}$$

here σ_{t0} represents the r.m.s width of the pulse ensemble. Inserting Eq. (3) into Eq. (2), we readily get

$$\Gamma^0\left(t_1,t_2\right)=\exp\left(-\frac{t_1^2+t_2^2}{4\sigma_{t0}^2}\right)\int p(v)\exp\left[-iv\left(t_1-t_2\right)\right]dv. \tag{4}$$

Comparing Eqs. (1) and (4), we can see that $\gamma^0\left(t_1,t_2\right)$ is the Fourier transform of $p(v)$.

Let us consider that a novel legitimate degree of coherence of the pulse is represented by convolution of two degrees of coherence γ_1 and γ_2, i.e. [12].

$$\gamma\left(t_1-t_2\right)=A_t\gamma_1\left(t_1-t_2\right)\otimes\gamma_2\left(t_1-t_2\right), \tag{5}$$

where the symbol $\otimes$ denotes the convolution operation and A_t is a normalization factor. It is known that the Fourier transform of the convolution of two functions is a product of their Fourier transforms, we get

$$p(v)=p_1(v)\,p_2(v), \tag{6}$$

where $p_1(v)$ and $p_2(v)$ are the Fourier transforms of γ_1 and γ_2, respectively.

Now, we illustrate the theory by employing the Gaussian Schell-model temporal correlation [1] and MSSM temporal correlation function [25] for γ_1 and γ_2,

$$\gamma_1\left(t_1-t_2\right)=\gamma_g\left(t_1-t_2\right)=\exp\left[-\frac{\left(t_1-t_2\right)^2}{2T_g^2}\right], \tag{7}$$

$$\gamma_2\left(t_1-t_2\right)=\gamma_s\left(t_1-t_2\right)=\frac{1}{B}\sum_{n=1}^{N}\frac{(-1)^{n-1}}{C_n}\sin c\left(\frac{t_1-t_2}{C_nT_s}\right), \tag{8}$$

with normalization factor $B=\sum_{n=1}^{N}(-1)^{n-1}/C_n$, here $C_n=\sqrt[m]{(2N-1)/\left[2^m(2N-2n+1)\right]}$ m being an arbitrary positive real number, where T_g is the classic Gaussian temporal correlation and T_s represents the sinc Schell-model temporal correlation, which determine the degree of coherence of the pulse ensemble. Then, the temporal degree of coherence of pulse source γ_c, i.e. the convolution of the two degree of coherence γ_1 and γ_2 can be expressed as

$$\begin{aligned}\gamma_c\left(t_1-t_2\right) &= A_t\gamma_g\left(t_1-t_2\right)\otimes\gamma_s\left(t_1-t_2\right)\\ &= A_t\exp\left[-\frac{\left(t_1-t_2\right)^2}{2T_g^2}\right]\otimes\frac{1}{B}\sum_{n=1}^{N}\frac{(-1)^{n-1}}{C_n}\sin c\left(\frac{t_1-t_2}{C_nT_s}\right),\end{aligned} \tag{9}$$

which is similar to the form of the complex input field of a uniform pulse in [25], here $\gamma_g\left(t_1-t_2\right)=\exp\left[-\frac{\left(t_1-t_2\right)^2}{2T_g^2}\right]$ is supposed to be the temporal envelope of the degree of coherence of the pulse source.

Fig. 1 illustrates the variation of the degree of coherence γ_g,γ_s and their convolution γ_c on the time tag t_2-t_1 for different values of order N when $T_s=0.1$ ps and $T_g=0.04$ ps, respectively. Fig. 1(a-2) and (b-2) show that the temporal degree of coherence γ_s of multi-sinc Schell-model pulse exhibit oscillations, which is similar to the sinc Schell-model pulsed source of the second kind [22]. As a result of the convolution operation defined by Eq. (9), the oscillations of the temporal degree of coherence weaken as in Fig. 1(a-3) and (b-3), which implies that such form of the degree of coherence in the source field can realize the modulation of pulse propagation in second-order dispersive medium.

3. Propagation of the modulated pulse

Propagation of the mutual coherence function of the pulse source in second-order dispersive medium can be characterized by the generalized Collins formula in the temporal domain [15]

$$\begin{aligned}\Gamma\left(t_1,t_2,z\right)&=\frac{1}{2\pi\beta_2 z}\iint\Gamma^{(0)}\left(t_{10},t_{20}\right)\\ &\times\exp\left\{\frac{i}{2\pi\beta_2 z}\left[\left(t_{10}^2-t_{20}^2\right)-2\left(t_{10}t_1-t_{20}t_2\right)+\left(t_1^2-t_2^2\right)\right]\right\}dt_{10}dt_{20},\end{aligned} \tag{10}$$

where β_2 represents the group velocity dispersion coefficient.

Inserting Eq. (4) into Eq. (10) and interchanging the orders of integrals, we can obtain the expression

$$\Gamma\left(t_1,t_2,z\right)=\int p(v)\,H^*\left(t_1,z,v\right)H\left(t_2,z,v\right)dv, \tag{11}$$

where

$$\begin{aligned}H^*\left(t_1,z,v\right)H\left(t_2,z,v\right)&=\frac{1}{2\pi\beta_2}\iint H_0^*\left(t_1,v\right)H\left(t_2,v\right)\\ &\times\exp\left\{\frac{i}{2\pi\beta_2 z}\left[\left(t_{10}^2-t_{20}^2\right)-2\left(t_{10}t_1-t_{20}t_2\right)+\left(t_1^2-t_2^2\right)\right]\right\}dt_{10}dt_{20}.\end{aligned} \tag{12}$$

On substituting from Eq. (3) into Eq. (12), the following analytic formula can be obtained

$$\begin{aligned}&H^*\left(t_1,z,v\right)H\left(t_2,z,v\right)\\ &=\frac{\sigma_{t0}}{\Delta(z)}\exp\left[-\frac{\sigma_{t0}^2}{4\beta_2^2z^2}\left(t_1-t_2\right)^2+\frac{i}{2\beta_2 z}\left(t_1^2-t_2^2\right)\right]\\ &\quad\times\exp\left\{-\left[\frac{t_1+t_2}{2}+\frac{i\sigma_{t0}^2}{2\beta_2 z}\left(t_1-t_2\right)-2\pi\beta_2 zv\right]/\Delta^2(z)\right\},\end{aligned} \tag{13}$$

where $\Delta^2(z)=\sigma_{t0}^2+\beta_2^2z^2/\sigma_{t0}^2$.

By taking the Fourier transform of Eqs. (7) and (8) and using Eq. (6), we get

$$\begin{aligned}p(v)&=p_g(v)\,p_s(v)\\ &=\sqrt{2\pi T_g^2}\exp\left(-2\pi^2T_g^2v^2\right)\frac{T_s}{B}\sum_{n=1}^{N}(-1)^{n-1}rect\left(C_nT_sv\right).\end{aligned} \tag{14}$$

According to Eq. (13) the average intensity of pulse ensemble can be determined at the coinciding time instants:

$$I(t,z)=\Gamma(t,t,z)=\int p(v)\,F(t,z,v)\,dv, \tag{15}$$

where

$$F(t,z,v)=\frac{\sigma_{t0}^2}{\Delta(z)}\exp\left[-\left(t-2\pi\beta_2 zv\right)^2/\Delta^2(z)\right]. \tag{16}$$

From Eq. (15), we can see that $p(v)$ determines the profile of the intensity of pulse ensemble on propagation in second-order dispersive medium. When $p(v)$ is given by the Fourier transform of Eq. (8)

$$p_s(v)=\frac{T_s}{B}\sum_{n=1}^{N}(-1)^{n-1}rect\left(C_nT_sv\right), \tag{17}$$