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# Spectra shifts of a chirped Gaussian pulsed beam propagating in slant atmosphere path

Yan Dong[a,b], Yansong Song[a], Keyan Dong[a,*], Shuai Chang[a]

[a] National and Local Joint Engineering Research Center of Space Optoelectronics Technology, Changchun University of Science and Technology, Changchun, 130022, China

[b] School of Electronics and Information Engineering, Changchun University of Science and Technology, Changchun 130022, China

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ABSTRACT

Based on the extended Huygens-Fresnel principle, the cross-spectral density function of a chirped Gaussian pulsed beam propagating in slant atmosphere path was derived, and the spectra shift properties of chirped Gaussian pulsed beam in slant atmosphere path were studied. The results show that the on-axis spectral shifts may be red shift comparing to the spectra at the source plane L = 0, while the off-axis spectra shifts is blue shift. The results also show that the red shift or the blue shift of chirped Gaussian pulsed beam in slant atmosphere path will increase as the parameters $C_0$ and $\alpha$ of slant atmosphere increase.

## 1. Introduction

In recent years, more and more laser beams have been applied to the atmospheric optics, and the propagation properties of various laser beams in atmosphere have been studied due to which have applications in the field of laser radar, laser imaging system and free-space optical communications. The influences of turbulent atmosphere on the propagation properties of laser beams are widely analyzed [1]. And many types of laser beam propagation in turbulent atmosphere are also been investigated, such as vortex beam [2], partially coherent crescent-like optical beam [3], four-petal Gaussian beams [4], partially coherent four-petal Gaussian vortex beams [5], pulsed Laguerrian beam [6], flat-topped vortex hollow beam [7], radial phased-locked partially coherent anomalous hollow beam array [8], spectrally partially coherent Gaussian Schell-model pulsed beam [9] et al. In the applications of laser beam in atmosphere, the propagation properties of beams in slant path is a hot topic. The propagation properties of laser beams in slant atmosphere path have been widely studied, such as partially coherent anomalous elliptical hollow Gaussian beam [10], Airy beam [11], partially coherent electromagnetic Gaussian-Schell model pulse beams [12], partially coherent Gaussian-Schell model beam [13], flattened-vortex beam [14], partially coherent Hermite-Gaussian beam [15], general multi-Gaussian beam [16], J(0)-correlated partially coherent beam [17], single photon [18], and Laguerre-Gaussian beam [19] et al. In the studies of beams in slant atmosphere, pulsed beam have been studied. Recently, the propagation properties of chirped Gaussian pulsed beam were also widely studied [20–22]. While, the spectra shifts of chirped Gaussian pulsed beam in slant atmosphere path has not been reported. In this paper, the propagation equation of chirped Gaussian pulsed beam propagating in slant atmosphere has been derived, and the influences of slant atmosphere path on the spectra shifts of chirped Gaussian pulsed beam are studied.

* Corresponding author.
*E-mail address:* dongkeyan2018@sohu.com (K. Dong).

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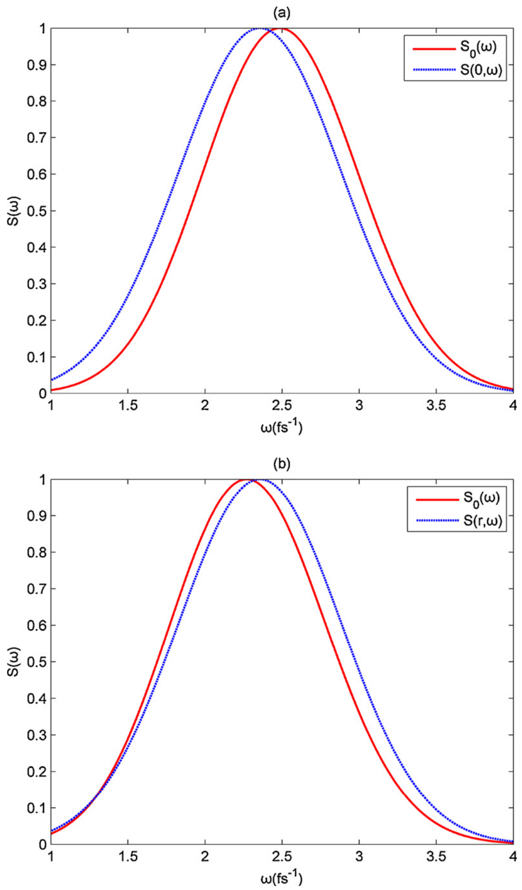


**Fig. 1.** Normalized spectra of chirped Gaussian pulsed beam propagating in slant atmosphere path. (a) on-axis (0), (b) off axis ($r = 4cm$).

## 2. Chirped Gaussian pulsed beam propagating in slant atmosphere

In the space-frequency domain, the chirped Gaussian pulsed beam propagating along the z-axis at the source plane L = 0 can be written as [20]:

$$E(\mathbf{r}_0, 0, \omega) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{x_0^2 + y_0^2}{w^2}\right)\sqrt{\frac{T^2(1 - iC)}{1 + C^2}} \exp\left[-\frac{T^2(1 - iC)}{2(1 + C^2)}(\omega - \omega_0)^2\right] \tag{1}$$

where $\mathbf{r}_0 = (x_0, y_0)$ denotes the vector at the source plane L = 0; $w$ is the beam radius of the Gaussian beam; $\omega_0$ is the central angular frequency; T is the pulse duration; C is the chirp parameter.

Based on the extended Huygens-Fresnel diffraction principle, the cross-spectral density function of chirped Gaussian pulsed beam propagation in slant atmosphere path at the propagation distance $L$ can be expressed as [10–14]:

$$W(\mathbf{r},\mathbf{r}, L, \omega) = \frac{k^2}{4\pi^2 L^2} \iint d\mathbf{r}_{10} d\mathbf{r}_{20} E(\mathbf{r}_{10}, 0, \omega) E^*(\mathbf{r}_{20}, 0, \omega) \times \exp\left[-\frac{ik}{2L}(\mathbf{r}\text{-}\mathbf{r}_{10})^2 + \frac{ik}{2L}(\mathbf{r}\text{-}\mathbf{r}_{20})^2\right] \times \langle \exp[\psi(\mathbf{r}_{10},\mathbf{r}) + \psi^*(\mathbf{r}_{20},\mathbf{r})]\rangle \tag{2}$$

Where $\mathbf{r} = (x,y)$ represents the position vectors at receive plane; $k = 2\pi/\lambda$ is the wave number with $\lambda$ being the wavelength; the asterisk denotes the complex conjugation; $\psi(\mathbf{r}_0, \mathbf{r}, z)$ is the solution to the Rytov method that describe the slant atmosphere path. And

$$\langle \exp[\psi(x_{10}, y_{10}, x, y) + \psi^*(x_{20}, y_{20}, x, y)]\rangle = \exp\left[-\frac{(x_{10} - x_{20})^2 + (y_{10} - y_{20})^2}{\rho_0^2}\right] \tag{3}$$

with $\rho_0$ is the coherence of a spherical wave propagating in slant atmosphere path, and which can be written as

$$\rho_0 = \left[1.46k^2 \int_0^L C_n^2(z)\left(1 - \frac{z}{L}\right)dz\right]^{-3/5} \tag{4}$$

where $C_n^2(z\cos\alpha)$ is the refractive index structure parameter in slant atmosphere, and $\alpha$ represents the zenith angle. The $C_n^2(z\cos\alpha)$ can be expressed as [23,24]