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Propagation of supercontinuum laser sources in a slant path through the atmosphere

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ABSTRACT

Taking the atmospheric refraction, extinction and turbulence into account, the propagation characteristic of supercontinuum laser sources in a slant path through the turbulent atmosphere is investigated. The effect of spectral width, initial spot size and zenith angle in a slant path on the beam width and propagation efficiency are studied in details. Numerical examples reveal that the beam width and propagation efficiency are different values while the spectral width varies. With the zenith angle in a slant atmospheric path increasing, the beam width of supercontinuum laser sources will increase and propagation efficiency will decrease. The initial spot size has an optimal value when spectral width and zenith angle are fixed.

1. Introduction

Supercontinuum (SC) laser sources can produce directional broadband light by making use of cascaded nonlinear optical interactions in an optical fiber. With the increasing of the average output power [1–3], the applications of SC laser sources in many fields become practicable, such as hyperspectral LiDAR and free-space optical communications [4,5]. These applications require SC laser sources propagate through the atmosphere in a slant path. And SC laser sources propagation in the atmosphere will be affected by many factors, including atmospheric refraction, extinction and turbulence. In recent years, some experimental studies related to the propagation of SC laser sources in turbulent atmosphere have been carried out [6–9]. However, to the best of our knowledge, there is no work related with SC laser sources propagating through the atmosphere when the effects of atmosphere are taken into account all together.

In this paper, we investigate the propagation of SC laser sources in turbulent atmosphere in a slant path. Our main goal is to show how to use SC laser sources to improve the system performance. It is based on the factors that how to select the initial spot size and spectral width of SC laser.

2. Theory analysis

Let us consider a Gaussian beam with a single-wavelength λ, the long time averaged intensity distribution at propagation distance z has a profile of the form [10]

$$I(x, y, z, \lambda) = I_0(\lambda)\frac{T(\lambda, z)R_0^2(\lambda)}{R^2(z, \lambda)} \times \exp\left(-\frac{2[(x - x_0(z, \lambda))^2 + (y - y_0(z, \lambda))^2]}{R^2(z, \lambda)}\right) \quad (1)$$

where $I_0(\lambda) = P_0(\lambda)/[\pi R_0^2(\lambda)/2]$ is the peak intensity, $P_0(\lambda)$ is the power of the Gaussian beam. The $R_0(\lambda) = \chi d_0(\lambda)$ represent the spot size after expanding, $d_0(\lambda)$ is the initial spot size at the output of fiber, χ is the expand ratio of the expanding system. $T(\lambda, z) \approx \exp[\ln[T_0(\lambda, z)]\sec\zeta]$ is the transmittance when $\zeta < \pi/4$, and $T_0(\lambda, z)$ is the transmittance when $\zeta = 0$. $x_0(z, \lambda) = y_0(z, \lambda) = \theta(\lambda)z$ is the position of beam centroid resulting from the atmospheric refraction. The refraction integrals $\theta(\lambda)$ is given by [11]

$$\theta(\lambda) = \int_{n_d}^{n_u} \frac{n_d r_0 \sin\zeta/n^2}{r_e\sqrt{[1 - n_d r_0 \sin\zeta/(n r_0)]}} dn \quad (2)$$

where r_e is the radius of the earth, n_d and n_u are the refractive index of atmosphere at the beginning and end of propagating path.

The long time averaged spot $R(z, \lambda)$ at propagation distance z can be written as [10]

$$R(z, \lambda) = [{R_0}^2(\lambda) + \Theta_{\text{spread}}^2(\lambda)z^2]^{1/2} \quad (3)$$

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The spreading angle Θ_{spread} contains contributions from several parts including diffraction Θ_{diff}, beam quality $\Theta_{quality}$ and atmospheric turbulence Θ_{turb}. For describing the effects of atmosphere on the laser beam propagation, we can write the spreading angle in the form as

$$\Theta_{spread}(\lambda) = [\Theta^2_{diff}(\lambda) + \Theta^2_{quality}(\lambda) + \Theta^2_{turb}(\lambda)]^{1/2} \quad (4)$$

The diffraction angle of a single-mode beam is $\Theta_{diff}(\lambda) = \lambda/[\pi R_0(\lambda)]$. And the total diffraction angle is $\Theta_{diff}(\lambda) + \Theta_{quality}(\lambda) = [M^2(\lambda)]^2\Theta_{diff}(\lambda)$, where $M^2(\lambda)$ is the beam propagation factor of the spectral component at wavelength λ.

The influence of the atmospheric turbulence is mainly determined by the coherent length. The spreading angle of Gaussian beams due to atmospheric turbulence can be written as [12]

$$\theta^2_{tur}(\lambda) = 2\left[\frac{\lambda}{\pi\rho_0(\lambda, z)}\right]^2 \quad (5)$$

where $\rho_0(\lambda, z) = [0.545\bar{C}^2_n(2\pi/\lambda)^2 z]^{-3/5}$ is the coherent length of spherical wave and $\bar{C}^2_n = \sec\zeta\int_0^H C^2_n(h)dh/z$ is the average structure constant of the refraction index. In this paper the Hufnagel–Valley 5/7 model is used to describe the model of the structure constant $C^2_n(h)$ and can be expressed as

$$C^2_n(h) = 3.593\times10^{-53}h^{10}e^{-h/1000} + 2.7\times10^{-16}e^{-h/1500} + 1.7\times10^{-14}e^{-h/100} \quad (6)$$

The total optical field of SC laser sources can be expressed as the superposition of optical fields of each spectral component, which is written as

$$I(x, y, z) = \int_0^\infty I(x, y, z, \lambda)d\lambda = \int_0^\infty \frac{2T(\lambda, z)P_0(\lambda)}{(\pi R^2(z, \lambda))} \times \exp\left(-\frac{2[(x - x_0(z, \lambda))^2 + (y - x_0(z, \lambda))^2]}{R^2(z, \lambda)}\right)d\lambda \quad (7)$$

According to the second-moment method, we can calculate the width of optical beam at distance z. The centroid of the beam can be derived as

$$\bar{x} = \bar{y} = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} xI(x, y, z)dxdy}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I(x, y, z)dxdy} = \frac{\int_0^\infty x_0(z, \lambda)T(z, \lambda)P_0(\lambda)d\lambda}{\int_0^\infty T(z, \lambda)P_0(\lambda)d\lambda} \quad (8)$$

We can obtain the root-mean-square (rms) beam width as

$$w(z) = w_x(z) = w_y(z) = 2\left[\frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}(x - \bar{x})^2 I(x, y, z)dxdy}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I(x, y, z)dxdy}\right]^{1/2} = 2\left[\frac{\int_0^\infty T(z, \lambda)P_0(\lambda)(R^2(z, \lambda) + 4x_0^2(z, \lambda))/4d\lambda}{\int_0^\infty T(z, \lambda)P_0(\lambda)d\lambda - \bar{x}^2}\right]^{1/2} \quad (9)$$

The propagation efficiency is defined the ratio of power in the circle to all transmitted power and expressed as

$$\eta(z) = \frac{\int_{x'_0-a}^{x'_0+a}\int_{y'_0-a}^{y'_0+a} I(x, y, z)dxdy}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I(x, y, 0)dxdy} = \frac{\int_0^\infty T(z, \lambda)P_0(\lambda)\left[1 - \exp\left(\frac{-2[a + x'_0 - x_0(z, \lambda)]^2}{R^2(z, \lambda)}\right)\right]d\lambda}{\int_0^\infty P_0(\lambda)d\lambda} \quad (10)$$

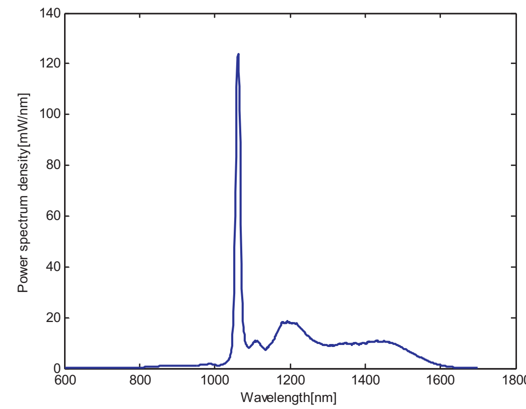

Fig. 1. Power spectral density of the SC beam with average output power 6.8 W.

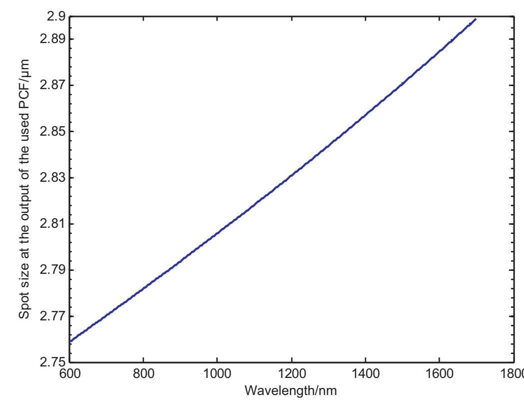

Fig. 2. Spot size of SC beam output from the used PCF as a function of wavelength.

where a is the radius, and $x'_0 = y'_0 = x_0(z, \lambda_{center})$ is the center of the circle, λ_{center} is the middle wave of the SC laser.

3. Numerical examples

As a numerical example, the power spectrum density of a SC laser with average output power 6.8 W is shown in Fig. 1. The spectrum covers the range from 600 nm to 1700 nm [13].

The output of SC laser is close to diffraction-limited ($M^2 = 1.2$). The spot size $d_0(\lambda)$ at the output end of PCF can be calculated by using COMSOL software. The dependence of $d_0(\lambda)$ on wavelength is shown in Fig. 2. It is supposed that the expand ratio χ is independence on wavelength, so the dependence of $R_0(\lambda) = \chi d_0(\lambda)$ and $d_0(\lambda)$ on wavelength are the same.

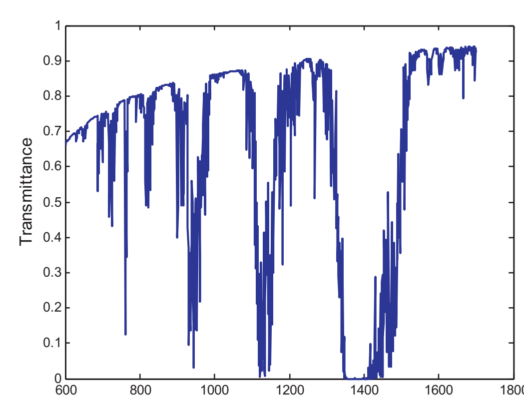

Fig. 3. Transmittance for different wavelengths when the zenith angle is zero.