Propagation Properties of Multi-Gaussian Schell-Model Beams through Oceanic Turbulence

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Abstract　Based on the model developed recently for describing a spatial power spectrum function of clear oceanic water and the extended Huygens-Fresnel integral in linear media, the effects of oceanic turbulence on propagation properties of a multi-Gaussian Schell-model (MGSM) beam is studied. The analytic expressions such as the spectral density, the degree of coherence and the propagation factor M^2 of the beam are derived. Numerical results show that, the oceanic turbulence has a significant influence on propagation properties of a MGSM beam. With the suitable choice of beam parameters, the center of the intensity profile not only forms a plateau in the far-field but also the formed plateau can keep a long distance in oceanic turbulence. Furthermore, a MGSM beam with a large source parameter N could further reduce turbulence-induced spreading effect.

Key words　oceanic optics, multi-Gaussian Schell-model beams, degree of coherence, propagation factor M^2, oceanic turbulence

OCIS codes　010.4450; 010.4455; 010.7060; 30.1670

多高斯-谢尔模型光束在海洋湍流中的传输特性研究

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摘要　基于最近发展的描述海洋湍流的空间功率谱函数和线性介质中广义惠更斯-菲涅耳积分公式,推导了多高斯-谢尔模型光束的光强、相干度及光束质量分子 M^2 的解析表达式,研究了海洋湍流对多高斯-谢尔模型光束传输特性的影响。数值计算结果表明,海洋湍流对多高斯-谢尔模型光束传输特性有着重要影响。适当地选择光束参数,在远场光强不仅可以形成平顶分布,而且这种平顶分布在湍流中能够保持相当长的距离,并且多高斯-谢尔模型光束的级次 N 越大,湍流诱导的光束扩展越小。

关键词　海洋光学;多高斯-谢尔模型光束;相干度;M^2 传播因子;海洋湍流

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1　Introduction

The propagation properties of many types of laser beams in free space and in turbulent media have been studied extensively due to their wide application such as polarization remote sensing, coherent optical communication, etc.[1-8]. It is shown that partially coherent beams are less sensitive to that of fully coherent beams[9-10], so much attention have been paid to propagation of partially coherent beams through atmosphere turbulence. Also, a few of papers have been focused on propagation of beams in ocean,

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biological issues, optical fibers, chiral media, etc.[11-20]. However, among partially coherent beams in the previous literatures, the one which satisfies a set of physically meaningful conditions and enjoys a comprehensive version is Gaussian Schell-model beams, the other models of beams have just remained of purely academic interest.

Recently, a multi-Gaussian Schell-model (MGSM) beam has been introduced[21], whose intensity profile is Gaussian function but the degree of spectral coherence is a sum of suitably weighted Gaussian functions with different variances and sign-alternating heights. The realizable condition for a MGSM beam has been derived[22]. The most important property of a MGSM beam is that the initial intensity has a Gaussian profile, but its intensity distribution evolves gradually into a flat-topped profile in far field. The behavior of the polarization properties of a MGSM beam in free space and in image-forming optical system were reported, and propagation of a MGSM beam through ABCD optical systems was studied[23]. The second-order moments of the wigner distribution function of a MGSM beam in turbulent atmosphere were investigated[24]. The scintillation index of a multi-Gaussian Schell-model beam in turbulent atmosphere was discussed[25]. However, as far as we know, the issue concerning the propagation of a MGSM beam in turbulent ocean has not yet been reported. A laser beam is used in underwater medium sometimes, communication among the divers, submarines, ships, sensors and the unmanned underwater vehicles requiring high data rates brings the necessity of employing optical communications rather than the acoustical communications. Hence, it becomes important to research how oceanic turbulence affects on the propagation properties of a MGSM beam.

In this paper, we explore propagation properties of a MGSM beam through oceanic turbulence. With the model developed recently for describing a spatial power spectrum function of clear oceanic water turbulence[14,15] and the extended Huygens-Fresnel integral in linear media, the analytic expressions for the spectral density and the degree of coherence are derived. Then, employing the second-order moments of beams and some mathematical skills, the propagation factor of the beam is obtained. The trends of the beam characteristics with numerical examples are analyzed.

2 Propagation of MGSM beam through oceanic turbulence

2.1 Matrix elements of a MGSM beam propagating through oceanic turbulence

Adopting one-dimensional representation, the cross-spectral density of the MGSM beam covering two distinct points of the source plane can be expressed as

$$W^{(0)}(x'_1, x'_2, 0) = \frac{1}{C_0}\exp\left(-\frac{x'^2_1 + x'^2_2}{4\sigma^2}\right)\sum_{m=1}^{N}\binom{N}{m}\frac{(-1)^{m-1}}{m}\exp\left[-\frac{(x'_1 - x'_2)^2}{2m\delta^2}\right], \tag{1}$$

where the parameter σ is the transverse beam width of the source, δ denotes the r. m. s. correlation width, while x'_1 and x'_2 are two different coordinates along the x axis. $C_0 = \sum_{m=1}^{N}\binom{N}{m}\frac{(-1)^{m-1}}{m}$ is the normalization factor, $\binom{N}{m}$ represents binomial coefficients. The condition which can generate a beam-like field for the MGSM source is same as that for the Gaussian-schell model sources:

$$\frac{1}{4\sigma^2} + \frac{1}{\delta^2} \leqslant \frac{2\pi^2}{\lambda^2}, \tag{2}$$

where λ is the wavelength of the source, under the paraxial approximation and by Huygens-Fresnel integral, the cross-spectral density through oceanic turbulence for a MGSM beam in the half-space $z > 0$ can be expressed as

$$W(x_1,x_2,z)=\frac{k}{2\pi z}\iint W^{(0)}(x'_1,x'_2,0)\cdot\zeta(x_1,x_2,x'_1,x'_2,z)\mathrm{d}x'_1\mathrm{d}x',\tag{3}$$

where k denotes the wave number, ζ is the propagator given by the expression[26] in the random medium:

$$\zeta(x_1,x_2,x'_1,x'_2,z)=\exp\left[-\mathrm{i}k\frac{(x_1-x'_1)^2-(x_2-x'_2)^2}{2z}\right]\langle\exp[\psi^*(x_1,x'_1)+\psi^*(x_2,x'_2)]\rangle_m.\tag{4}$$

equation (4) consists of two terms, the first term describes the effect of the free-space diffraction on the beam, and second term takes the form[27]

$$\langle\exp[\psi^*(x_1,x'_1)+\psi^*(x_2,x'_2)]\rangle_m=\exp\{T(z)[(x_1-x_2)^2+(x_1-x_2)(x'_1-x'_2)+(x'_1-x'_2)^2]\},\tag{5}$$

where $T(z)=\dfrac{\pi^2k^2z}{3}\int_0^\infty k^3\varphi_n(k)\mathrm{d}k$, $\varphi_n(k)$ is the spatial power spectrum of refractive-index fluctuations.

The power spectrum of turbulence fluctuations of the oceanic water has been developed recently in literatures specifically for isotropic and homogeneous oceanic turbulence, as a linearized polynomial of two variables: the temperature fluctuations and the salinity fluctuations. A particular case is considered here, when the eddy thermal diffusivity and the diffusion of the salt are equal. Then

$$\varphi_n(k)=0.388\times10^{-8}\varepsilon^{-\frac{1}{3}}k^{-\frac{11}{3}}[1+2.35(k\eta)^{\frac{2}{3}}]f(k,\zeta,\chi_\mathrm{T}),\tag{6}$$

where ε is the rate of dissipation of turbulent kinetic energy per unit mass of fluid which may vary in the range from 10^{-1} to 10^{-10} $\mathrm{m}^2\cdot\mathrm{s}^{-3}$, $\eta=10^{-3}$ m being the Kolmogorov micro scale (inner scale), and

$$f(k,\zeta,\chi_\mathrm{T})=\frac{\chi_\mathrm{T}}{\zeta^2}[\zeta^2\exp(-A_\mathrm{T}\tau)+\exp(-A_\mathrm{S}\tau)-2\zeta\exp(-A_\mathrm{TS}\tau)],\tag{7}$$

with χ_T being the rate of dissipation of mean-square temperature taking value in the range from 10^{-4} to 10^{-10} $\mathrm{K}^2\cdot\mathrm{s}^{-1}$, $A_\mathrm{T}=1.863\times10^{-2}$, $A_\mathrm{S}=1.9\times10^{-4}$, $A_\mathrm{TS}=9.41\times10^{-3}$, $\tau=8.284(k\eta)^{4/3}+12.978(k\eta)^2$, ζ (non-dimensional) being the relative strength of temperature and salinity fluctuations, which can vary in the interval of [−5, 0] in the ocean waters, −5 value corresponding to the case when temperature-induced optical turbulence is dominated, and 0 corresponding to the situation when salinity-driven turbulence prevails. In order to illustrate these typical dependence on oceanic parameters ε, χ_T and ζ clearly, the numerical results are plotted in Fig. 1. It is seen that the parameters of ε and χ_T mainly affect the attitude of the power spectrum, and the balance parameter ζ influences its shape and height. Figure 1(a) reveals that the smaller the values of ε, the lower the height for power the spectrum. Figures 1(b) and 1(c) show that the bigger the values of χ_T or ζ, higher the altitude of it, and ζ also affects its shape. It means there are the larger values of χ_T and ζ, smaller values of ε, and the stronger of the turbulence.

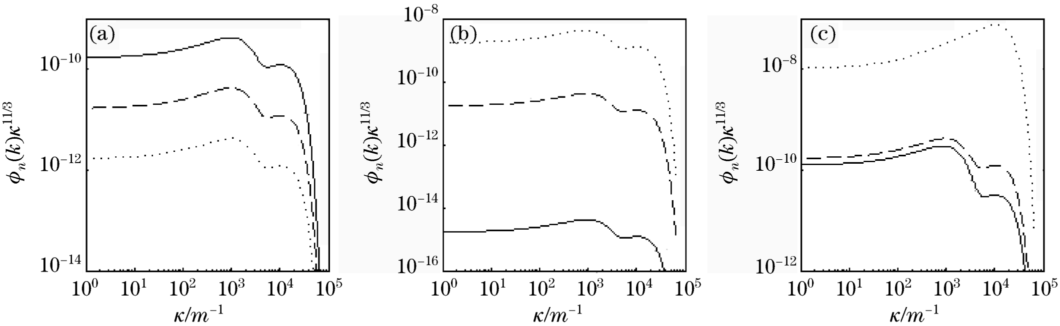

Fig. 1 Log-log plot of the spatial power spectrum $\Phi_n(k)$ for several values of ε, χ_T and ζ, calculated from Eq. (6) and normalized by the Kolmogorov power-law $k^{-11/3}$. (a) $\varepsilon=10^{-10}$ (solid curves), $\varepsilon=10^{-7}$ (dashed curves), $\varepsilon=10^{-4}$ (dotted curves) while $\chi_\mathrm{T}=10^{-5}$ and $\zeta=-2.5$; (b) $\chi_\mathrm{T}=10^{-10}$ (solid curves), $\chi_\mathrm{T}=10^{-6}$ (dashed curves), $\chi_\mathrm{T}=10^{-4}$ (dotted curves) while $\varepsilon=10^{-10}$ and $\zeta=-2.5$; (c) $\zeta=-4.9$ (solid curves), $\zeta=-2.5$ (dashed curves), $\zeta=-0.1$ (dotted curves) while $\varepsilon=10^{-10}$ and $\chi_\mathrm{T}=10^{-5}$

By substituting Eqs. (4) and (5) into Eq. (3) and performing mathematical calculation, we can obtain a formula of the cross-spectral density for a MGSM beam propagating in turbulent ocean as follows:

$$W(x_1,x_2,z)=\frac{1}{C_0}\sum_{m=1}^{N}\binom{N}{m}\frac{(-1)^{m-1}}{m\cdot\Delta_m(z)^2}\exp\left[-\frac{(x_1+x_2)^2}{8\sigma^2\Delta_m(z)^2}\right]\cdot$$
$$\exp\left\{-\frac{\mathrm{i}k}{2z}\left[\frac{1}{\Delta_m(z)^2}+\left(\frac{Q_m^2}{\Delta_m(z)^2}-1\right)T(z)\right](x_2^2-x_1^2)\right\}\times \tag{8}$$
$$\exp\left\{\left[\frac{Q_m^2T(z)^2}{2}-T(z)-\frac{1}{2Q_m^2\cdot\Delta_m(z)^2}(1+Q_m^2T(z))^2\right](x_2-x_1)^2\right\},$$

with

$$Q_m^2=\left[\frac{1}{4\sigma^2}+\frac{1}{m\delta^2}+2T(z)\right]^{-1}, \tag{9}$$

$$\Delta_m(z)^2=1+\frac{z^2}{\sigma^2Q_m^2k^2}, \tag{10}$$

2.2　Average spectral density and spectral degree of coherence

Setting $x_1=x_2=x$, we derive the average spectral density of a MGSM beam propagating through oceanic turbulence

$$S(x,z)=\frac{1}{C_0}\sum_{m=1}^{N}\binom{N}{m}\frac{(-1)^{m-1}}{m\cdot\Delta_m(z)^2}\exp\left[-\frac{x^2}{2\sigma^2\Delta_m(z)^2}\right], \tag{11}$$

According to the unified theory of coherence and polarization, the spectral degree of coherence for the beam at a pair of coordinates x_1 and x_2 can be defined by

$$\mu(x_1,x_2,z)=\frac{W(x_1,x_2,z)}{\sqrt{S(x_1,z)\cdot S(x_2,z)}}. \tag{12}$$

Substituting Eqs. (8)-(11) into Eq. (12) and considering a specific situation when $x_1=-x_2=x$, we have

$$\mu(x,-x,z)=\frac{\sum_{m=1}^{M}\binom{N}{m}\frac{(-1)^{m-1}}{m\cdot\Delta_m(z)^2}\exp\left\{\left\{2Q_m^2T(z)^2-4T(z)-\frac{2}{Q_m^2\cdot\Delta_m(z)^2}[1+Q_m^2T(z)]^2\right\}x^2\right\}}{\sum_{m=1}^{M}\binom{N}{m}\frac{(-1)^{m-1}}{m\cdot\Delta_m(z)^2}\exp\left[-\frac{x^2}{2\sigma^2\Delta_m(z)^2}\right]}, \tag{13}$$

2.3　Second-moments and propagation factor

The second-order intensity moments for a monochromatic light beam in frame of one-dimensional cartesian coordinate are defined as

$$[x^2]=\frac{\int_{-\infty}^{\infty}x^2S(x,z)\mathrm{d}x}{\int_{-\infty}^{\infty}S(x,z)\mathrm{d}x}, \tag{14}$$

$$(u^2)=\frac{\int_{-\infty}^{\infty}\frac{\partial W(x_1,x_2,z)}{\partial x_1\partial x_2}\Big|_{x_1=x_2=x}\mathrm{d}x}{k^2\int_{-\infty}^{\infty}S(x,z)\mathrm{d}x}, \tag{15}$$

$$(xu)=\frac{\int_{-\infty}^{\infty}\left[x_1\frac{\partial W(x_1,x_2,z)}{\partial x_2}-x_2\frac{\partial W(x_1,x_2,z)}{\partial x_2}\right]\Big|_{x_1=x_2=x}\mathrm{d}x}{2\mathrm{i}k^2\int_{-\infty}^{\infty}S(x,z)\mathrm{d}x}. \tag{16}$$

In order to describe the spreading of a MGSM beam affected by oceanic turbulence, we employ the propagation factor which was introduced by Siegman[28] and can be define in terms of the second-order moments as follow:

$$M^2=2k([x^2][u^2]-[xu]^2)^{\frac{1}{2}}. \tag{17}$$

After tedious integral but straightforward calculations, we can obtain

$$M^2=2k\left\{\sum_{m=1}^{N}\binom{N}{m}\frac{(-1)^{m-1}\sigma^2}{m}\Delta_m(z)\cdot\sum_{m=1}^{N}\binom{N}{m}\frac{(-1)^{m-1}\sigma R_2(z)}{m}+\left[\sum_{m=1}^{N}\binom{N}{m}\frac{(-1)^{m-1}\sigma^2R_1(z)}{m}\right]^2\right\}^{\frac{1}{2}}\times$$

$$\left[\sum_{m=1}^{N}\binom{N}{m}\frac{(-1)^{m-1}}{m\cdot\Delta_m(z)}\right]^{-\frac{1}{2}},\tag{18}$$

with

$$R_1(z)=[1+(Q_m^2\text{-}\Delta(z)^2)T(z)],\tag{19}$$

$$R_2(z)=\frac{\sigma^2}{z^2}R_1(z)\frac{1}{Q_m^2\Delta(z)^2k^2}+\frac{2}{k}[1+T(z)].\tag{20}$$

3 Numerical example and analysis

Here the numerical results of propagation properties of the MGSM beam propagating in the oceanic turbulence are illustrated by using the analytical formulas. The common calculation parameters are chosen as $\lambda=632.8$ nm, $\sigma=2$ cm, $\delta=1$ mm unless they are specified in the particular condition. One finds from Eq. (11) that the profile of the MGSM beam is a superposition of different weighted Gaussian functions with different variances and sign-alternating amplitudes as expected. We calculate the variation of the spectral density versus transverse coordinate x at the plane $z=1$ km for several values of oceanic parameters ε, ζ and χ_T with different beam parameter N in oceanic turbulence. Form Figs. 2～4, we clearly see that, when $N=1$, all solid curves described distributions of the spectral density of a Gaussian-schell beam. When oceanic turbulence gradually becomes strong, that is, when values of ζ and χ_T increase or value of ε reduces, the spectral density goes to weaken due to spreading effect of the beam in oceanic turbulence. With the increase of parameter N, the center of the intensity profile appears plateaus, and the larger the value of N is, the wider the plateau becomes. However, the influence of oceanic turbulence on the distribution of spectral density for a MGSM beam is to damage the central flat of intensity. The stronger the oceanic turbulence, the more obvious the damage. The different oceanic parameters affect differently on the intensity profile, the parameters ζ and χ_T play more of a role than the parameter ε. The numerical results also show that, when ε changes in the range from 10^{-1} to 10^{-7}, and ζ varyies in the interval $[-5;-2.5]$, it is almost the same as that of a MGSM beam in free space for profiles of the spectral density. Under this condition, the oceanic turbulence is so weak that the influence on the beam can be ignored.

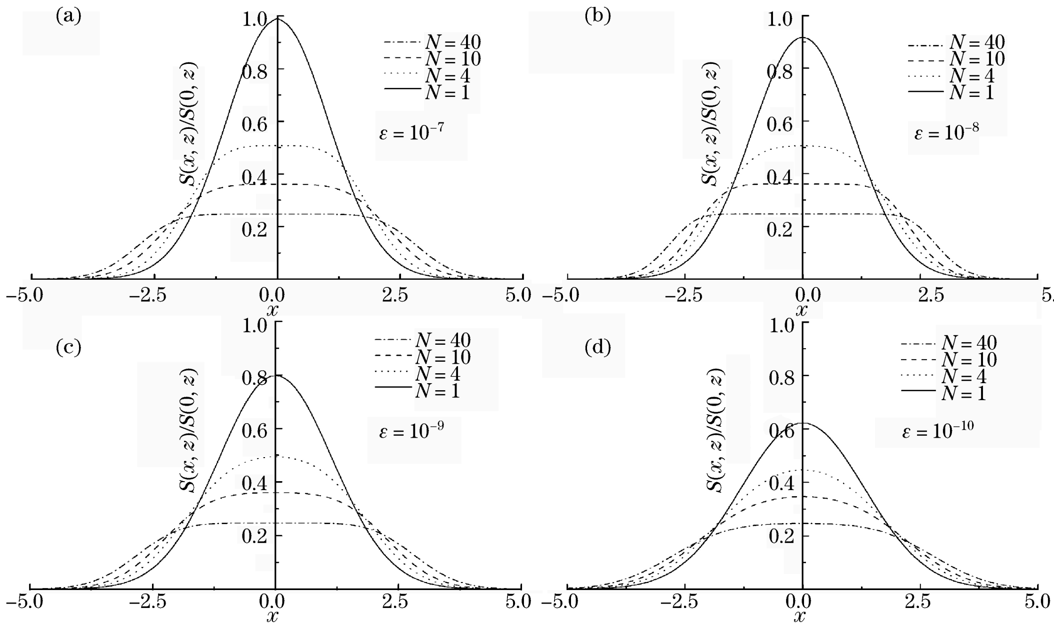

Fig. 2 Variation of the spectral density of a MGSM beam with transverse coordinate x at $z=1$ km for several values of parameters ε and N with $\zeta=2.5$, $\chi_T=10^{-10}$ in oceanic turbulence

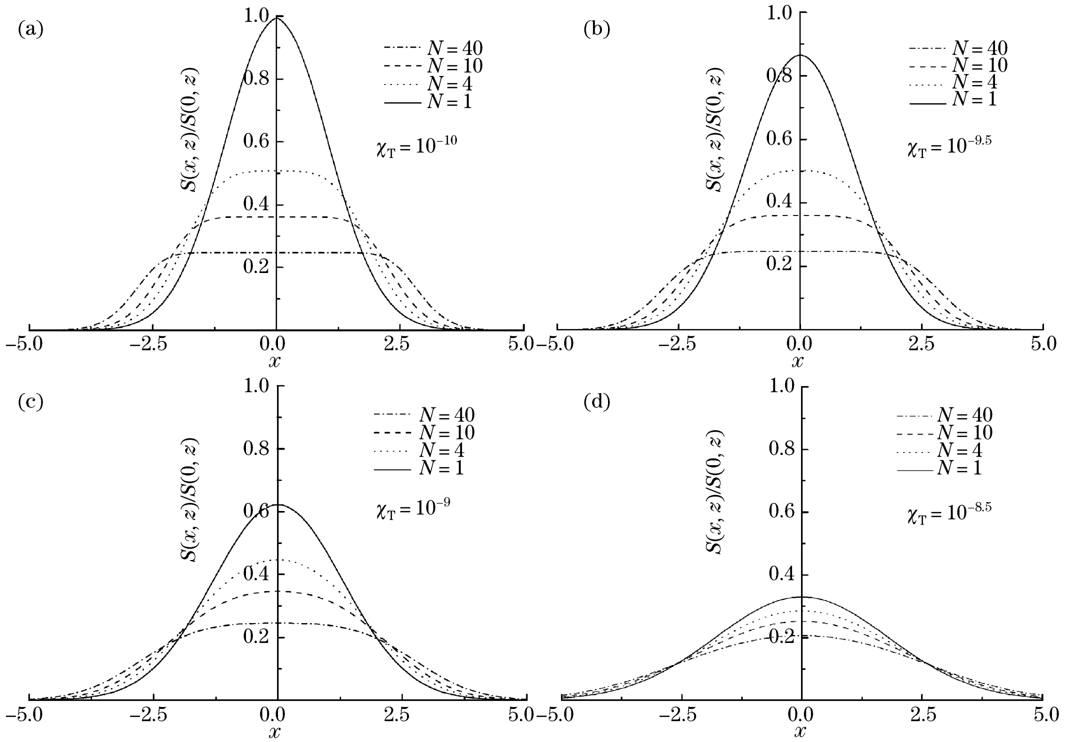

Fig. 3 Variation of the spectral density of a MGSM beam with transverse coordinate x at $z=1$ km for several values of parameters χ_T and N with $\zeta=2.5$, $\varepsilon=10^{-3}$ in oceanic turbulence

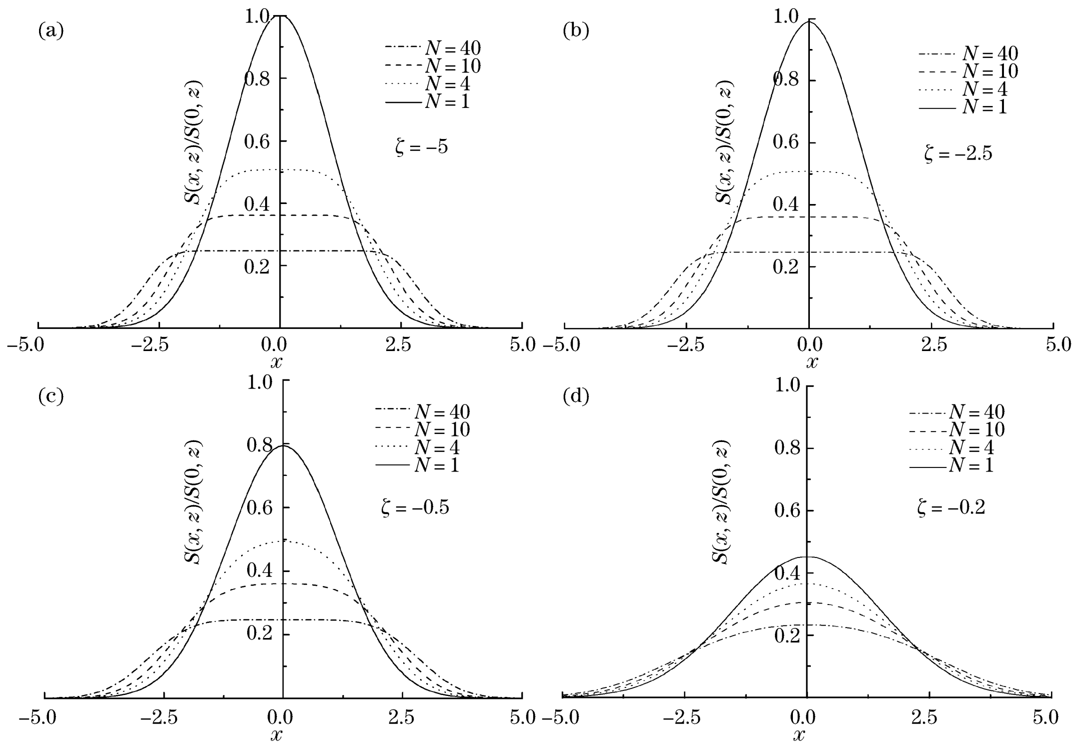

Fig. 4 Variation of the spectral density of a MGSM beam with transverse coordinate x at $z=1$ km for several values of parameters ζ and N with $\chi_T=10^{-10}$, $\varepsilon=10^{-3}$ in oceanic turbulence

Figure 5 illustrates the evolution of spectral degree of coherence for a MGSM beam at several propagation distances in oceanic turbulence. From Fig. 5, we can find that, at relatively short distance from the source [see Figs. 5(a) and (b)], for the larger parameter N, spectral degree of coherence of the beam is narrower. With the increase of the propagation distance, the effect of the oceanic turbulence on the beam becomes strong, the spectral degree of coherence of the beam broadens gradually. When propagation distance is greater than 1 km, all the curves evolve into Gaussian profiles with monotonically increasing variance [see Figs. 5(c) and (b)].

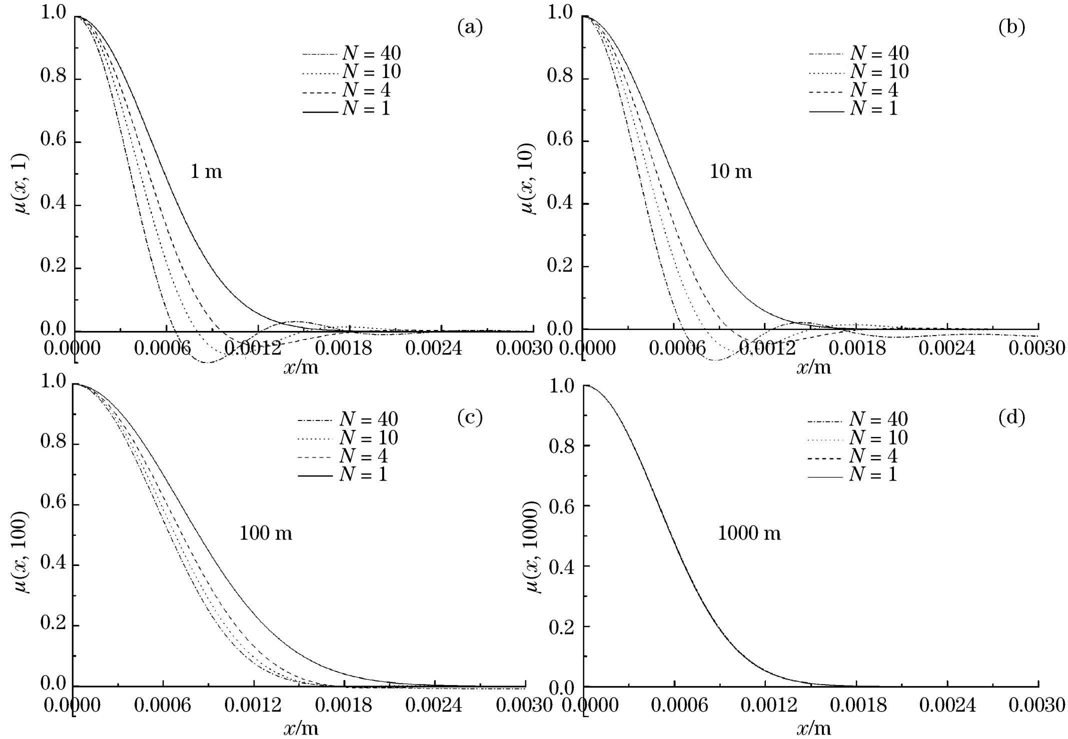

Fig. 5 Spectral degree of coherence of a MGSM beam versus transverse coordinate x for several different distances with $\varepsilon=10^{-3}$, $\chi_T=10^{-10}$, $\zeta=2.5$ in oceanic turbulence

Figure 6 describes the effects of oceanic turbulence on the spectral degree of coherence at the plane $z=$

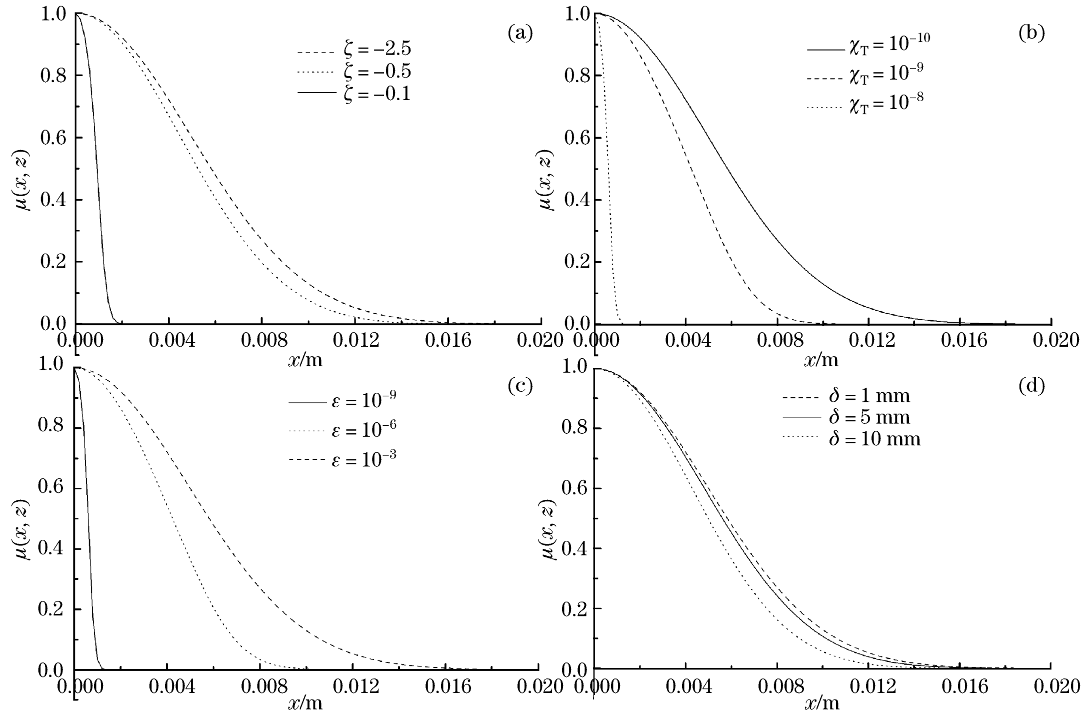

Fig. 6 Spectral degree of coherence of a MGSM beam versus transverse coordinate x at $z=1$ km for several values of oceanic parameters (a) ζ, (b) χ_T, (c) ε and (d) different correlation widths δ with $N=10$ in oceanic turbulence

1 km for several different values of oceanic parameters and source parameters. It is shown from Fig. 6 that the distribution of spectral degree of coherence narrows down sharply for a large values of the parameters ζ and χ_T, in which the oceanic turbulence impacts on the beam strongly, the behavior of spectral degree of coherence is the same for small values of the parameter ε, but for the large correlation widths of the source δ, it is a little narrow for the spectral degree of coherence.

Figure 7 shows dependence of normalized propagation factor M^2 of a MGSM beam on the oceanic turbulence parameters and the beam parameter at propagation distance $z=1$ km. For the convenience of comparison, the parameters of a MGSM beam with $N=10$ are chosen as $\varepsilon=10^{-3}$, $\chi_T=10^{-10}$, $\zeta=-2.5$, $\delta=1$ mm, and then the change of propagation factor M^2 is analyzed when one parameter varies and the other parameters are fixed. From Fig. 7, we also see that the propagation factor M^2 increases sharply in strong oceanic turbulence such as large values of χ_T and ζ, or small value of ε. However, for large value of correlation width δ, the propagation factor M^2 increases rapidly.

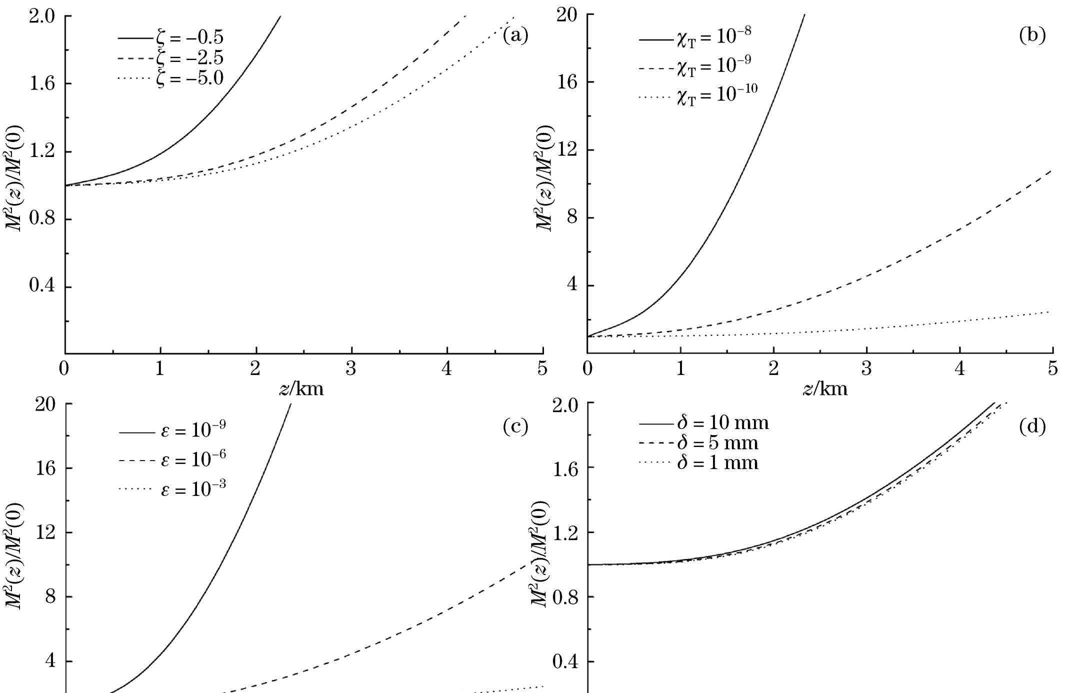

Fig. 7 Normalized propagation factor $M^2(z)/M^2(0)$ of a MGSM beam versus propagation distance z for several values of oceanic parameters (a) ζ, (b) χ_T, (c) ε, and (d) different correlation widths δ with $N=10$ in oceanic turbulence

Figure 8 plots variation of normalized propagation factor M^2 with propagation distance z and parameter N in oceanic turbulence for a MGSM beam, respectively. From Fig. 8(a), we can find that propagation factor M^2 increases with increasing the propagation distance z quickly. Furthermore, the advantage of propagation factor M^2 with smaller parameter N over these with larger parameters N is enhanced, particularly at a long propagation distance. Figure 8(b) describes effect of the oceanic turbulence parameter ε on propagation factor M^2 at propagation distance $z=1$ km. From it, we can also find that, with the increase of the source parameter N, the propagation factor M^2 decreases graduanlly, moreover, when oceanic turbulence becomes strong, which means that the value of parameter ε is smaller, the affection on propagation factor M^2 is larger.

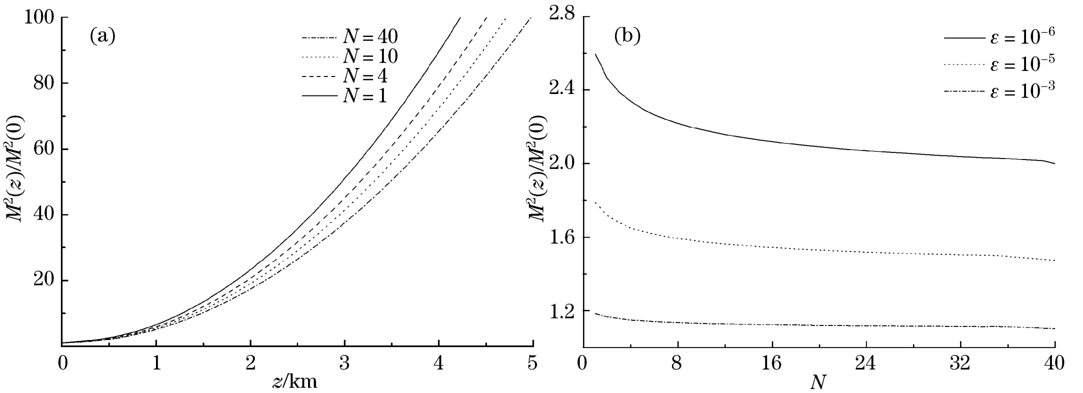

Fig. 8 Normalized propagation factor $M^2(z)/M^2(0)$ of a MGSM beam versus propagation distance z and beam parameter N in oceanic turbulence, respectively, for (a) several values of source parameter N with $\varepsilon=10^{-6}$, $x_T=10^{-9}$, $\zeta=2.5$, $\delta=1$ cm and (b) several values of the oceanic parameter ε with $x_T=10^{-9}$, $\zeta=2.5$, $\delta=1$ cm at $z=1$ km

4 Conclusion

The propagation characteristics of a multi-Gaussian Schell-model (MGSM) beam through oceanic turbulence are researched. We derive the analytic expressions for the cross-spectral density of the beam based on the extended Huygens-Fresnel integral, and deduce the expressions for the spectral density and the spectral degree of coherence. Furthermore, employing second-order intensity moments for a monochromatic light beam, we obtain formula of the propagation factor for a MGSM beam. Numerical results indicate that, both source parameters and oceanic turbulence models impact on the propagation behavior of the beam. For spectral density, with the suitable choice of beam parameters, the intensity profile of the beam not only forms plateau in the far-field but also this plateau can keep a long distance in oceanic turbulence. Compared with correlation width, the spectral degree of coherence seems more sensitive to slight change in values of the oceanic parameters. However, so far as propagation factor, it increases sharply in strong oceanic turbulence. Moreover, numerical results also show that influence of oceanic turbulence on the MGSM beam with a large N is less than that with a small N.

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