第37卷 第1期
2013年1月

激 光 技 术
LASER TECHNOLOGY

Vol. 37, No. 1
January, 2013

文章编号: 1001-3806(2013)01-0114-04

正交余弦光栅的衍射场

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摘要: 为了研究正交余弦光栅的衍射场,采用波前相因子判断法并考虑到光栅孔径的影响,对正交余弦光栅的衍射进行了理论分析,得到了正交余弦光栅衍射场所含基元成分,导出了像面波前函数、像面振幅分布函数和光强分布函数,并得出主焦斑的半角宽度。结果表明,该研究可为光栅用于光学信息处理技术提供理论依据。

关键词: 衍射与光栅; 波动光学; 正交余弦光栅; 波前相因子; 衍射场

中图分类号: O435　　**文献标识码:** A　　**doi:** 10.7510/jgjs.issn.1001-3806.2013.01.028

Diffraction field of orthogonal cosine-gratings

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Abstract: In order to analyze diffraction field of orthogonal cosine-gratings, it was analyzed based on the method of wave-front phase factors and considering the influence of limited aperture of grating. The phase-front function, amplitude and intensity expressions of the diffraction field were deduced. The amplitude and intensity of light distribution diagram of phase plane were obtained. Finally, the half-angle-width of maximum value in the center was given. This study may further provide a theoretical foundation to analyze diffraction of orthogonal cosine-gratings.

Key words: diffraction and gratings; wave optics; orthogonal cosine-grating; wave-front phase factor; diffraction field

引　言

目前,光滤波技术、超光成像技术、光学信息处理技术等都涉及到有限孔径的衍射、选频、成像等问题,而对于有限孔径的近场和远场的研究,常常只能选用一些近似的方法来处理问题,例如用半波带法和矢量法,半定性、半定量地分析问题[1]。因此,有一些定量结果无法得到。本研究是在惠更斯-菲涅耳原理的基础上,用波前相因子判断法对正交余弦光栅的近场和远场进行研究,使问题更加严密直观。

1　波前相因子判断法

一个衍射系统如图1所示,其中 $\widetilde{U}_1(x_0,y_0,0)$ 为入射光波到达衍射屏的波前函数,$\widetilde{U}_2(x_0,y_0,0)$ 是衍射屏的后场初端的波前函数,$\widetilde{U}(x,y,z)$ 是接收屏的

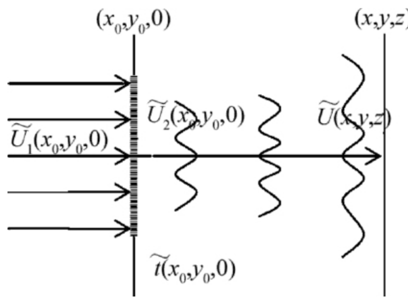

Fig. 1　Diffraction field

波前函数。入射光波前 $\widetilde{U}_1(x_0,y_0,0)$ 被衍射屏变成出射光波前 $\widetilde{U}_2(x_0,y_0,0)$,是衍射屏的作用,由其屏函数 $\widetilde{t}(x_0,y_0,0)$ 来决定; 出射光波前 $\widetilde{U}_2(x_0,y_0,0)$ 沿传播方向到某处的波前 $\widetilde{U}(x,y,z)$,是波衍射的问题,原则上来说,衍射波的波前可以根据菲涅耳-基尔霍夫衍射积分公式得出,然而这种积分运算相当复杂。如果能把复杂的衍射波看成若干平面波和球面波的组合,使复杂问题变成简单波场的叠加,再用菲涅耳-基尔霍夫衍射积分公式导出衍射波的波前 $\widetilde{U}(x,y,z)$ 就简单多了。

所谓波前相因子判断法,就是根据波前函数的相因子,判断波的主要成分,分析衍射波的主要特征,再用菲涅耳-基尔霍夫衍射积分公式计算衍射波的波前 $\widetilde{U}(x,y,z)$。

基金项目: 云南省质量工程资助项目; 保山学院科研、教研基金重点资助项目(10B002K)

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收稿日期: 2012-03-30; 收到修改稿日期: 2012-06-07

2　正交余弦光栅

当两张余弦光栅紧密地叠放在一起，其条纹正交，称之为正交余弦光栅。如图 2 所示，两张余弦光栅 G_1 和 G_2，其栅纹垂直叠放在一起。

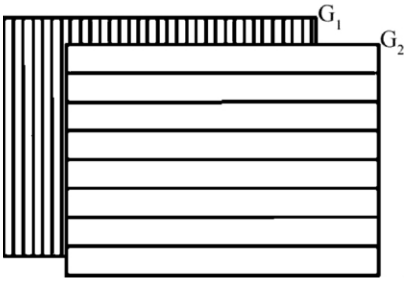

Fig. 2　Orthogonal cosine-gratings

G_1 和 G_2 衍射屏函数的形式分别为：

$$G_1:\ \tilde{t}_{01}{}'(x_0) = t_{01} + t_1\cos(2\pi f_1 x_0 + \varphi_0) \qquad (1)$$

$$G_2:\ \tilde{t}_{02}{}''(y_0) = t_{02} + t_2\cos(2\pi f_2 y_0 + \varphi_0{}') \qquad (2)$$

3　正交余弦光栅夫琅禾费衍射场

正交余弦光栅夫琅禾费衍射的实验装置如图 3 所示。用平行光照射正交余弦光栅，在透镜的后焦面上接收到的衍射是一个 2 维衍射场。

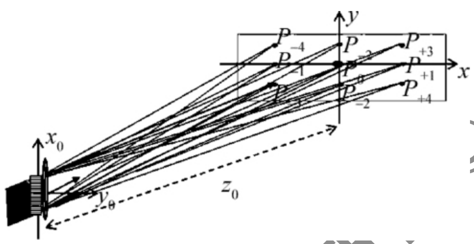

Fig. 3　Diffraction fields of orthogonal cosine-gratings

当正交余弦光栅为一个衍射屏时，则其屏函数为：

$$\tilde{t}_0(x_0,y_0,0) = \tilde{t}_{01}{}'(x_0)\cdot\tilde{t}_{02}{}''(x_0) = t_{01}\cdot t_{02} + t_{02}t_1\cos(2\pi f_1x_0) + t_{01}t_2\cos(2\pi f_2x_0) + \frac{1}{2}t_1t_2\cos[2\pi(f_1x_0+f_2y_0)] + \frac{1}{2}t_1t_2\cos[2\pi(f_1x_0-f_2y_0)] \qquad (3)$$

把(1)式和(2)式代入(3)式计算时，取 $\varphi_0 = \varphi_0{}' = 0$。

薄透镜的变换函数形式为[2-4]：

$$\tilde{t}_{03}{}'(x_0,y_0,0) = \exp\left(-\mathrm{i}k\frac{x_0^2+y_0^2}{2z_0}\right) \qquad (4)$$

正交余弦光栅和透镜组合在一起的变换函数为：

$$\tilde{t}(x_0,y_0,0) = \tilde{t}_0(x_0,y_0,0)\exp\left(-\mathrm{i}k\frac{x_0^2+y_0^2}{2z_0}\right) \qquad (5)$$

当用波长为 λ、振幅为 A_0 的一束平行光照射这正交余弦光栅时，则出射光波前为：

$$\widetilde{U}_2(x_0,y_0,0) = A_0\exp\left(-\mathrm{i}k\frac{x_0^2+y_0^2}{2z_0}\right)\cdot \left\{\left[t_{01}\cdot t_{02} + t_{02}t_1\cos(2\pi f_1x_0) + t_{01}t_2\cos(2\pi f_2x_0) + \frac{1}{2}t_1t_2\cos[2\pi(f_1x_0+f_2y_0)] + \frac{1}{2}t_1t_2\cos[2\pi(f_1x_0-f_2y_0)]\right]\right\} \qquad (6)$$

由此可见，它相当于是由 4 个余弦光栅和一个单缝组成的光学衍射系统。则(6)式可看成球面波照射到 4 个余弦光栅和单缝所组成的衍射系统上。

设 $\gamma_1 = \frac{t_1}{t_{01}}$，$\gamma_2 = \frac{t_2}{t_{02}}$，$A_1 = A_0t_{01}t_{02}$（$\gamma$ 可称其为振幅衬比度，其取值范围为 $0<\gamma\leqslant 1$），由欧拉公式得出这波前包含 9 种成分：

$\widetilde{U}_0(x_0,y_0,0) = A_1\exp\left(-\mathrm{i}k\frac{x_0^2+y_0^2}{2z_0}\right)$，$\widetilde{U}_{+1}(x_0,y_0,0) = \frac{\gamma_1}{2}A_1\exp\left(-\mathrm{i}k\frac{x_0^2+y_0^2}{2z_0}\right)\exp(\mathrm{i}2\pi f_1x_0)$，$\widetilde{U}_{-1}(x_0,y_0,0) = \frac{\gamma_1}{2}A_1\exp\left(-\mathrm{i}k\frac{x_0^2+y_0^2}{2z_0}\right)\exp(-\mathrm{i}2\pi f_1x_0)$，$\widetilde{U}_{+2}(x_0,y_0,0) = \frac{\gamma_2}{2}A_1\exp\left(-\mathrm{i}k\frac{x_0^2+y_0^2}{2z_0}\right)\exp(\mathrm{i}2\pi f_2y_0)$，$\widetilde{U}_{-2}(x_0,y_0,0) = \frac{\gamma_2}{2}A_1\exp\left(-\mathrm{i}k\frac{x_0^2+y_0^2}{2z_0}\right)\exp(-\mathrm{i}2\pi f_2y_0)$，$\widetilde{U}_{+3}(x_0,y_0,0) = \frac{\gamma_1\gamma_2}{4}A_1\exp\left(-\mathrm{i}k\frac{x_0^2+y_0^2}{2z_0}\right)\exp[\mathrm{i}2\pi(f_1x_0+f_2y_0)]$，$\widetilde{U}_{-3}(x_0,y_0,0) = \frac{\gamma_1\gamma_2}{4}A_1\exp\left(-\mathrm{i}k\frac{x_0^2+y_0^2}{2z_0}\right)\times\exp[-\mathrm{i}2\pi(f_1x_0+f_2y_0)]$，$\widetilde{U}_{+4}(x_0,y_0,0) = \frac{\gamma_1\gamma_2}{4}A_1\times\exp\left(-\mathrm{i}k\frac{x_0^2+y_0^2}{2z_0}\right)\exp[2\pi(f_1x_0-f_2y_0)]$，$\widetilde{U}_{-4}(x_0,y_0,0) = \frac{\gamma_1\gamma_2}{4}A_1\exp\left(-\mathrm{i}k\frac{x_0^2+y_0^2}{2z_0}\right)\exp[-\mathrm{i}2\pi(f_1x_0-f_2y_0)]$。

用波前相因子判断法得出 $\widetilde{U}_0(x_0,y_0,0)$，$\widetilde{U}_{+1}(x_0,y_0,0)$，$\widetilde{U}_{-1}(x_0,y_0,0)$，$\widetilde{U}_{+2}(x_0,y_0,0)$，$\widetilde{U}_{-2}(x_0,y_0,0)$，$\widetilde{U}_{+3}(x_0,y_0,0)$，$\widetilde{U}_{-3}(x_0,y_0,0)$，$\widetilde{U}_{+4}(x_0,y_0,0)$，$\widetilde{U}_{-4}(x_0,y_0,0)$ 这 9 种基元成分为 9 列会聚球面波，它们分别会聚于衍射屏 P_0，P_{+1}，P_{+2}，P_{+3}，P_{+4}，P_{-1}，P_{-2}，P_{-3}，P_{-4} 处，如图 3 所示。然而，事情的复杂性来自于正交余弦光栅有限孔径的影响。

在傍轴条件下，近似处理振幅传播因子，取 $\frac{1}{r}\approx\frac{1}{z}$，$\mathrm{d}s = \mathrm{d}x_0\mathrm{d}y_0$，根据菲涅耳-基尔霍夫衍射积分表达式得到 9 列会聚球面波的衍射波前函数：

$$\widetilde{U}_0(x,y,z) = -\frac{\mathrm{i}}{\lambda z}\iint_{\Sigma_0} A_1\exp\left(-\mathrm{i}k\frac{x_0^2+y_0^2}{2z_0}\right)\times$$

$$\exp\left[\mathrm{i}k\left(z+\frac{x_0{}^2+y_0{}^2}{2z}+\frac{x^2+y^2}{2z}-\frac{xx_0+yy_0}{z}\right)\right]\mathrm{d}x_0\mathrm{d}y_0,$$

$$\widetilde{U}_{+1}(x,y,z)=-\frac{\mathrm{i}}{\lambda z}\iint_{\Sigma_0}\frac{\gamma_1}{2}A_1\exp\left(-\mathrm{i}k\frac{x_0{}^2+y_0{}^2}{2z_0}\right)\times \exp(\mathrm{i}2\pi f_1x_0)\exp\left[\mathrm{i}k\left(z+\frac{x_0{}^2+y_0{}^2}{2z}+\frac{x^2+y^2}{2z}-\frac{xx_0+yy_0}{z}\right)\right]\mathrm{d}x_0\mathrm{d}y_0,$$

$$\widetilde{U}_{-1}(x,y,z)=-\frac{\mathrm{i}}{\lambda z}\iint_{\Sigma_0}\frac{\gamma_1}{2}A_1\exp\left(-\mathrm{i}k\frac{x_0{}^2+y_0{}^2}{2z_0}\right)\times \exp(-\mathrm{i}2\pi f_1x_0)\exp\left[\mathrm{i}k\left(z+\frac{x_0{}^2+y_0{}^2}{2z}+\frac{x^2+y^2}{2z}-\frac{xx_0+yy_0}{z}\right)\right]\mathrm{d}x_0\mathrm{d}y_0,$$

$$\widetilde{U}_{+2}(x,y,z)=-\frac{\mathrm{i}}{\lambda z}\iint_{\Sigma_0}\frac{\gamma_2}{2}A_1\exp\left(-\mathrm{i}k\frac{x_0{}^2+y_0{}^2}{2z_0}\right)\times \exp(\mathrm{i}2\pi f_2y_0)\exp\left[\mathrm{i}k\left(z+\frac{x_0{}^2+y_0{}^2}{2z}+\frac{x^2+y^2}{2z}-\frac{xx_0+yy_0}{z}\right)\right]\mathrm{d}x_0\mathrm{d}y_0,$$

$$\widetilde{U}_{-2}(x,y,z)=-\frac{\mathrm{i}}{\lambda z}\iint_{\Sigma_0}\frac{\gamma_2}{2}A_1\exp\left(-\mathrm{i}k\frac{x_0{}^2+y_0{}^2}{2z_0}\right)\times \exp(-\mathrm{i}2\pi f_2y_0)\exp\left[\mathrm{i}k\left(z+\frac{x_0{}^2+y_0{}^2}{2z}+\frac{x^2+y^2}{2z}-\frac{xx_0+yy_0}{z}\right)\right]\mathrm{d}x_0\mathrm{d}y_0,$$

$$\widetilde{U}_{+3}(x,y,z)=-\frac{\mathrm{i}}{\lambda z}\iint_{\Sigma_0}\frac{\gamma_2}{2}A_1\exp\left(-\mathrm{i}k\frac{x_0{}^2+y_0{}^2}{2z_0}\right)\exp[\mathrm{i}2\pi(f_1x_0+f_2y_0)]\times \exp\left[\mathrm{i}k\left(z+\frac{x_0{}^2+y_0{}^2}{2z}+\frac{x^2+y^2}{2z}-\frac{xx_0+yy_0}{z}\right)\right]\mathrm{d}x_0\mathrm{d}y_0,$$

$$\widetilde{U}_{-3}(x,y,z)=-\frac{\mathrm{i}}{\lambda z}\iint_{\Sigma_0}\frac{\gamma_2}{2}A_1\exp\left(-\mathrm{i}k\frac{x_0{}^2+y_0{}^2}{2z_0}\right)\times \exp[-\mathrm{i}2\pi(f_1x_0+f_2y_0)]\exp\left[\mathrm{i}k\left(z+\frac{x_0{}^2+y_0{}^2}{2z}+\frac{x^2+y^2}{2z}-\frac{xx_0+yy_0}{z}\right)\right]\mathrm{d}x_0\mathrm{d}y_0,$$

$$\widetilde{U}_{+4}(x,y,z)=-\frac{\mathrm{i}}{\lambda z}\iint_{\Sigma_0}\frac{\gamma_1\gamma_2}{4}A_1\exp\left(-\mathrm{i}k\frac{x_0{}^2+y_0{}^2}{2z_0}\right)\times \exp[\mathrm{i}2\pi(f_1x_0-f_2y_0)]\exp\left[\mathrm{i}k\left(z+\frac{x_0{}^2+y_0{}^2}{2z}+\frac{x^2+y^2}{2z}-\frac{xx_0+yy_0}{z}\right)\right]\mathrm{d}x_0\mathrm{d}y_0,$$

$$\widetilde{U}_{-4}(x,y,z)=-\frac{\mathrm{i}}{\lambda z}\times \iint_{\Sigma_0}\frac{\gamma_1\gamma_2}{4}A_1\exp\left(-\mathrm{i}k\frac{x_0{}^2+y_0{}^2}{2z_0}\right)\exp[-\mathrm{i}2\pi(f_1x_0-f_2y_0)]\times \exp\left[\mathrm{i}k\left(z+\frac{x_0{}^2+y_0{}^2}{2z}+\frac{x^2+y^2}{2z}-\frac{xx_0+yy_0}{z}\right)\right]\mathrm{d}x_0\mathrm{d}y_0。$$

上面的积分号内都含有 x_0，y_0 2 次项因子和 1 次项因子，使得积分运算相当繁杂，难以用简单的解析函数表达出来。若只考虑像面上的衍射，问题就简单了。

4 正交余弦光栅在像面的衍射场

取 $z=z_0$，由上面 9 个积分式得正交余弦光栅在像面衍射的波前函数为：

$$\begin{aligned}U(x,y,z_0)=\Bigg\{&\left[\mathrm{sinc}\left(k\frac{x}{z_0}\frac{a}{2}\right)+\frac{\gamma_1}{2}\mathrm{sinc}\left(k\left(\lambda f_1-\frac{x}{z_0}\right)\frac{a}{2}\right)+\frac{\gamma_1}{2}\mathrm{sinc}\left(k\left(\lambda f_1+\frac{x}{z_0}\right)\frac{a}{2}\right)\right]\mathrm{sinc}\left(k\frac{y}{z_0}\frac{b}{2}\right)+\frac{\gamma_2}{2}\mathrm{sinc}\left(k\frac{x}{z_0}\frac{a}{2}\right)\times\\&\left[\mathrm{sinc}\left(k\left(\lambda f_2-\frac{y}{z_0}\right)\frac{b}{2}\right)+\frac{\gamma_2}{2}\mathrm{sinc}\left(k\left(\lambda f_2+\frac{y}{z_0}\right)\frac{b}{2}\right)\right]+\frac{\gamma_1\gamma_2}{4}\times\\&\left[\mathrm{sinc}\left(k\left(\lambda f_1-\frac{x}{z_0}\right)\frac{a}{2}\right)\mathrm{sinc}\left(k\left(\lambda f_2-\frac{y}{z_0}\right)\frac{b}{2}\right)+\mathrm{sinc}\left(k\left(\lambda f_1+\frac{x}{z_0}\right)\frac{a}{2}\right)\mathrm{sinc}\left(k\left(\lambda f_2+\frac{y}{z_0}\right)\frac{b}{2}\right)\right]+\\&\frac{\gamma_1\gamma_2}{4}\left[\mathrm{sinc}\left(k\left(\lambda f_1+\frac{x}{z_0}\right)\frac{a}{2}\right)\mathrm{sinc}\left(k\left(\lambda f_2-\frac{y}{z_0}\right)\frac{b}{2}\right)+\mathrm{sinc}\left(k\left(\lambda f_1-\frac{x}{z_0}\right)\frac{a}{2}\right)\mathrm{sinc}\left(k\left(\lambda f_2+\frac{y}{z_0}\right)\frac{b}{2}\right)\right]\Bigg\}A_2\mathrm{e}^{\mathrm{i}\varphi}\end{aligned}\tag{7}$$

式中，$A_2=\frac{A_1ab}{\lambda z_0}$，$\varphi=kz_0+k\frac{x^2+y^2}{2z_0}-\frac{\pi}{2}$。

根据(7)式得正交余弦光栅在 $z=z_0$ 处，衍射振幅分布函数(取正值)和光强分布函数为：

$$\begin{aligned}A(x,y,z_0)=A_2\Bigg[&\left[\mathrm{sinc}\left(k\frac{x}{z_0}\frac{a}{2}\right)+\frac{\gamma_1}{2}\mathrm{sinc}\left(k\left(\lambda f_1-\frac{x}{z_0}\right)\frac{a}{2}\right)+\frac{\gamma_1}{2}\mathrm{sinc}\left(k\left(\lambda f_1+\frac{x}{z_0}\right)\frac{a}{2}\right)\right]\mathrm{sinc}\left(k\frac{y}{z_0}\frac{b}{2}\right)+\\&\frac{\gamma_2}{2}\mathrm{sinc}\left(k\frac{x}{z_0}\frac{a}{2}\right)\left[\mathrm{sinc}\left(k\left(\lambda f_2-\frac{y}{z_0}\right)\frac{b}{2}\right)+\frac{\gamma_2}{2}\mathrm{sinc}\left(k\left(\lambda f_2+\frac{y}{z_0}\right)\frac{b}{2}\right)\right]+\\&\frac{\gamma_1\gamma_2}{4}\left[\mathrm{sinc}\left(k\left(\lambda f_1-\frac{x}{z_0}\right)\frac{a}{2}\right)\mathrm{sinc}\left(k\left(\lambda f_2-\frac{y}{z_0}\right)\frac{b}{2}\right)+\mathrm{sinc}\left(k\left(\lambda f_1+\frac{x}{z_0}\right)\frac{a}{2}\right)\mathrm{sinc}\left(k\left(\lambda f_2+\frac{y}{z_0}\right)\frac{b}{2}\right)\right]+\\&\frac{\gamma_1\gamma_2}{4}\left[\mathrm{sinc}\left(k\left(\lambda f_1+\frac{x}{z_0}\right)\frac{a}{2}\right)\mathrm{sinc}\left(k\left(\lambda f_2-\frac{y}{z_0}\right)\frac{b}{2}\right)+\mathrm{sinc}\left(k\left(\lambda f_1-\frac{x}{z_0}\right)\frac{a}{2}\right)\mathrm{sinc}\left(k\left(\lambda f_2+\frac{y}{z_0}\right)\frac{b}{2}\right)\right]\end{aligned}\tag{8}$$

$$I(x,y,z_0) = I_0\Bigg\{\Bigg[\mathrm{sinc}\left(k\frac{x}{z_0}\frac{a}{2}\right)+\frac{\gamma_1}{2}\mathrm{sinc}\left(k\left(\lambda f_1-\frac{x}{z_0}\right)\frac{a}{2}\right)+\frac{\gamma_1}{2}\mathrm{sinc}\left(k\left(\lambda f_1+\frac{x}{z_0}\right)\frac{a}{2}\right)\Bigg]\mathrm{sinc}\left(k\frac{y}{z_0}\frac{b}{2}\right)+$$
$$\frac{\gamma_2}{2}\mathrm{sinc}\left(k\frac{x}{z_0}\frac{a}{2}\right)\left[\mathrm{sinc}\left(k\left(\lambda f_2-\frac{y}{z_0}\right)\frac{b}{2}\right)+\frac{\gamma_2}{2}\mathrm{sinc}\left(k\left(\lambda f_2+\frac{y}{z_0}\right)\frac{b}{2}\right)\right]+$$
$$\frac{\gamma_1\gamma_2}{4}\left[\mathrm{sinc}\left(k\left(\lambda f_1-\frac{x}{z_0}\right)\frac{a}{2}\right)\mathrm{sinc}\left(k\left(\lambda f_2-\frac{y}{z_0}\right)\frac{b}{2}\right)+\mathrm{sinc}\left(k\left(\lambda f_1+\frac{x}{z_0}\right)\frac{a}{2}\right)\mathrm{sinc}\left(k\left(\lambda f_2+\frac{y}{z_0}\right)\frac{b}{2}\right)\right]+$$
$$\frac{\gamma_1\gamma_2}{4}\left[\mathrm{sinc}\left(k\left(\lambda f_1+\frac{x}{z_0}\right)\frac{a}{2}\right)\mathrm{sinc}\left(k\left(\lambda f_2-\frac{y}{z_0}\right)\frac{b}{2}\right)+\mathrm{sinc}\left(k\left(\lambda f_1-\frac{x}{z_0}\right)\frac{a}{2}\right)\mathrm{sinc}\left(k\left(\lambda f_2+\frac{y}{z_0}\right)\frac{b}{2}\right)\right]\Bigg\}^2 \quad (9)$$

式中，$I_0 = A_2{}^2 = \left(\frac{A_1 ab}{\lambda z_0}\right)^2$。

根据(8)式和(9)式得到相面上振幅和光强的分布图，如图 4 和图 5 所示。相关参量取值为：$\lambda = 630\mathrm{nm}$，$z_0 = 0.4\mathrm{m}$，$\gamma_1 = 0.8$，$\gamma_2 = 0.8$，$A_1 = 1$，$\lambda f_2 = 0.01$，$\lambda f_1 = 0.005$，$a = 20\mathrm{mm}$，$b = 20\mathrm{mm}$。

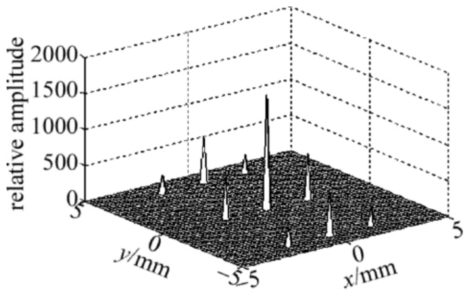

Fig. 4　Amplitude distribution of diffraction fields

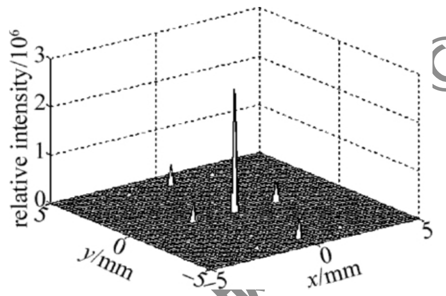

Fig. 5　Light distribution of diffraction fields

对于光栅的衍射，以往多有研究文献发表[10-13]，本文中以正交余弦光栅为轴对称的衍射屏为研究对象，揭示其衍射场所含成分，即 1 列平面衍射波和 8 列球面衍射波。从图 4 和图 5 中可以看出，在 P_0 点左右的轴向区间，会聚球面波 $\widetilde{U}_0(x,y,z_0)$ 项是主要贡献者；在 P_{+1} 点左右的轴向区间，会聚球面衍射波 $\widetilde{U}_{+1}(x,y,z_0)$ 项是主要贡献者。

考虑到正交余弦光栅孔径的限制，根据(8)式还可以得到中心主斑点的半角宽度为：$\Delta\theta_{0x} \approx \frac{\lambda}{a}$，$\Delta\theta_{0y} \approx \frac{\lambda}{b}$。

5　结　论

以上分析方法和半波带、矢量法相比较[14-16]，问题更加严密直观，克服了半波带法和矢量法的半定量、半定性分析方法的不足，并且所得结果和实验结果是一致的。

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