介质中4MFSS光场广义磁场的N_j次振幅压缩效应

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摘　要:根据量子力学中的态叠加原理,构造了强度不等的非对称四态叠加多模泛函叠加态光场(即4MFSS光场)。利用多模压缩态理论,对介质中4MFSS光场广义磁场分量的不等幂次高次振幅压缩效应进行了详细的研究。结果发现:①在一定条件下,上述4MFSS光场的广义磁场分量可呈现出周期性变化的广义非线性不等幂次高次振幅压缩效应;②上述4MFSS光场其广义磁场分量所呈现的N_j次方高次振幅效应的压缩幅度,明显受到介质的增益系数或吸收系数的直接影响;对于增益介质而言,随着传播距离的增大,光场N_j次方高次振幅压缩现象的压缩程度加深、压缩幅度增大、压缩效应增强;对于吸收介质而言,随着光场传播距离的增大,光场N_j次方高次振幅压缩现象的压缩程度降低、压缩幅度减小、压缩效应减弱。

关键词:4MFSS光场;增益介质;吸收介质;广义磁场;多模泛函叠加态;不等幂次振幅压缩
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由于多模压缩态光场[1-4]在多模非经典光场的制备与操控技术以及多纵模量子通信和量子光通信技术等高科技领域具有广阔的应用前景和重大的应用价值,因而引起了人们的极大关注和重视。近年来,人们从理想光场角度对多模叠加态的压缩及高次压缩特性做了大量而富有成效的研究工作[5-9],取得了一些可喜的成果。但是,对于介质中非对称四态叠加多模泛函叠加态光场的各种广义非线性等幂次与不等幂次高次压缩特性等,则未进行任何探讨。

鉴于此,本文利用新近建立的多模压缩态理论,对介质中4MFSS光场广义磁场分量的广义非线性不等幂次高次振幅压缩效应进行了详细的研究,由此得到了更为普遍的理论结果。

1　4MFSS光场$|\Psi^{(4)}(f_j)\rangle_q$的数学表达式

介质中沿Z轴方向传播的强度不对称的4*MFSS*(四态叠加多模泛函叠加态)光场$|\Psi(4)(f_j)\rangle_q$的数学表达式为

$$|\Psi(4)(f_j)\rangle_q = \sum_{k=1}^{4} C_K |\{f_j^{(K)}(x,y,z)e^{\alpha^{(K)}z}\}\rangle_q \tag{1}$$

式中:$\begin{cases} C_K = r_K\exp(i\theta_K) \\ f_j^{(K)}(x,y,z) = |f_j^{(K)}(x,y,z)|\exp[i\Phi_j^{(K)}(x,y,z)] \end{cases}$,$(K=1,2,3,4;j=1,2,\cdots,q)$;$C_K$为各态叠加的复几率幅;$\alpha^{(K)}$为增益或吸收系数;$f_j^{(K)}(x,y,z)$为各相干态的复解析函数。

多模相干态的数学表式为

$|\{f_j^{(K)}(x,y,z)e^{\alpha^{(K)}z}\}\rangle_q =$

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$$\exp\left\{-\frac{1}{2}\left[\sum_{j=1}^{q}|f_j^{(K)}(x,y,z)|^2 e^{\alpha^{(K)}z}\right]\right\}\sum_{|n_j|=0}^{\infty}\left\{\prod_{j=1}^{q}\left[\frac{(f_j^{(K)}(x,y,z))^{n_j}e^{n_j\alpha^{(K)}z}}{\sqrt{n_j!}}\right]\right\}|\{n_j\}\rangle_q \quad (2)$$

2 4MFSS 光场 $|\Psi(4)(f_j)\rangle_q$ 广义磁场的不等幂次振幅压缩的一般理论结果

根据多模辐射场的广义非线性不等幂次高次振幅压缩的定义[4]，并利用式(1)和式(2)，经大量计算可得到4MFSS光场广义磁场的不等次幂高次振幅压缩的一般理论结果如下：

$$Y_M = 4\langle \Delta Y_1^2(N_j)_q\rangle - \langle |A_q(N_j),A_q^+(N_j)|\rangle =$$

$$\frac{1}{q}\{2\langle\sum_{j,j'=1}^{q}a_j^{+N_j}a_{j'}^{N_{j'}}\rangle + \langle\sum_{j,j'=1}^{q}(a_j^{+N_j}a_{j'}^{+N_{j'}} + a_j^{N_j}a_{j'}^{+N_{j'}})\rangle - \langle\sum_{j=1}^{q}(a_j^{N_j}a_{j'}^{N_{j'}})\rangle^2\} =$$

$$\frac{2}{q}\{2\sum_{K=1}^{4}r_K^2\{\sum_{j=1}^{q}|f_j^{(K)}(x,y,z)|^{N_j}e^{N_j\alpha^{(K)}z}\cos[N_j\Phi_j^{(K)}(x,y,z)]\}^2+\sum_{K=1}^{3}\sum_{L=K+1}^{4}\{r_Kr_L\exp\{\sum_{j=1}^{q}[-\frac{1}{2}|(f_j^{(K)}(x,y,z)|^2$$
$$e^{2\alpha^{(K)}z}+|f_j^{(L)}(x,y,z)|^2e^{2\alpha^{(L)}z}+|f_j^{(K)}(x,y,z)f_j^{(L)}(x,y,z)|\ e^{(\alpha^{(K)}+\alpha^{(L)})z}\cos(\Phi_j^{(K)}(x,y,z)-\Phi_j^{(L)}(x,y,z))]\}$$
$$\{2\sum_{jj'=1}^{q}\{|\,|f_j^{(K)}(x,y,z)|^{N_j}|f_{j'}^{(L)}(x,y,z)|^{N_{j'}}e^{(N_j\alpha^{(K)}+N_{j'}\alpha^{(L)})z}\cos[(\theta_K-\theta_L)+\sum_{j=1}^{q}|f_j^{(K)}(x,y,z)f_j^{(L)}(x,y,z)|$$
$$e^{(\alpha^{(K)}+(\alpha^{(L)})z}\sin(\Phi_j^{(K)}(x,y,z)-(\Phi_j^{(L)}(x,y,z))+(N_j\Phi_j^{(K)}(x,y,z)-N_{j'}\Phi_{j'}^{(L)}(x,y,z))]\}+$$
$$\sum_{jj'=1}^{q}\{|\,|f_j^{(K)}(x,y,z)|^{N_j}|f_{j'}^{(K)}(x,y,z)|^{N_{j'}}e^{(N_j+N_{j'})\alpha^{(K)}z}\cos[(\theta_K-\theta_L)+\sum_{j=1}^{q}|f_j^{(K)}(x,y,z)f_j^{(L)}(x,y,z)|\ e^{(\alpha^{(K)}+\alpha^{(L)})z}$$
$$\sin(\Phi_j^{(K)}(x,y,z)-\Phi_j^{(L)}(x,y,z))+(N_j\Phi_j^{(K)}(x,y,z)+N_{j'}\Phi_{j'}^{(K)}(x,y,z))]\}+\sum_{jj'=1}^{q}\{|\,f_j^{(L)}(x,y,z)|^{N_j}$$
$$|f_{j'}^{(L)}(x,y,z)-|^{N_{j'}}e^{(N_j+N_{j'})\alpha^{(L)}z}\cos[(\theta_K-\theta_L)+\sum_{j=1}^{q}|f_j^{(K)}(x,y,z)f_j^{(L)}(x,y,z)|\ e^{(\alpha^{(K)}+\alpha^{(L)})z}$$
$$\sin(\Phi_j^{(K)}(x,y,z)-\Phi_j^{(L)}(x,y,z))-(N_j\Phi_j^{(L)}(x,y,z)+N_{j'}\Phi_{j'}^{(L)}(x,y,z))]\}\}\}-$$
$$2\{\sum_{K=1}^{4}\{r_K^2\{\sum_{j=1}^{q}|f_j^{(K)}(x,y,z)|^{N_j}e^{N_j\alpha^{(K)}z}\cos[N_j\Phi_j^{(K)}(x,y,z)]\}+\sum_{K=1}^{3}\sum_{L=K+1}^{4}\{r_Kr_L\exp\{\sum_{j=1}^{q}[-\frac{1}{2}(|f_j^{(K)}(x,y,z)|^2$$
$$e^{2\alpha^{(K)}z}+|f_j^{(L)}(x,y,z)|^2e^{2\alpha^{(L)}z}+|f_j^{(K)}(x,y,z)f_j^{(L)}(x,y,z)|\ e^{(\alpha^{(K)}+\alpha^{(L)})z}\cos(\Phi_j^{(K)}(x,y,z)-\Phi_j^{(L)}(x,y,z))]\}$$
$$\{\sum_{j=1}^{q}\{|\,f_j^{(K)}(x,y,z)|^{N_j}e^{(N_j\alpha^{(K)}z}\cos[(\theta_K-\theta_L)+\sum_{j=1}^{q}|f_j^{(K)}(x,y,z)f_j^{(L)}(x,y,z)|\ e^{(\alpha^{(K)}+\alpha^{(L)})z}$$
$$\sin(\Phi_j^{(K)}(x,y,z)-\Phi_j^{(L)}(x,y,z))+N_j\Phi_j^{(K)}(x,y,z)]\}+\sum_{j=1}^{q}\{|\,f_j^{(L)}(x,y,z)|^{N_j}e^{N_j\alpha^{(K)}z}\cos[(\theta_K-\theta_L)+$$
$$\sum_{j=1}^{q}|f_j^{(K)}(x,y,z)f_j^{(L)}(x,y,z)|\ e^{(\alpha^{(K)}+\alpha^{(L)})z}\sin(\Phi_j^{(K)}(x,y,z)-\Phi_j^{(L)}(x,y,z))-N_j\Phi_j^{(L)}(x,y,z)]\}\}\}^2\} \quad (3)$$

3 质中4MFSS光场 $|\Psi(f_j)\rangle_q$ 广义磁场的不等幂次高次振幅压缩效应

对于4MFSS光场 $|\Psi(4)(f_j)\rangle_q$，若各模的初始相位 $\Phi_j^{(K)}(x,y,z)$，$\Phi_j^{(L)}(x,y,z)$ 满足条件：

$$\left.\begin{aligned}N_j\Phi_j^{(K)}(x,y,z) &= \pm n_j^{(K)}\pi+\frac{\pi}{2}\\ N_j\Phi_j^{(L)}(x,y,z) &= \pm n_j^{(L)}\pi+\frac{\pi}{2}\end{aligned}\right\}\quad (j=1,2,\cdots,q;\ n_j^{(K)},n_j^{(L)}=0,1,\cdots) \quad (4)$$

3.1 $n_j^{(K)}$ 与 $n_j^{(L)}$ 同时取偶数或者取奇数时的情况

1）如果 $\sum_{j=1}^{q}|f_j^{(K)}(x,y,z)|^{N_j}e^{N_j\alpha^{(K)}z}=\sum_{j=1}^{q}|f_j^{(L)}(x,y,z)|^{N_j}e^{N_j\alpha^{(L)}z}$，则式(3)可化为：$Y_M=0$。即4MFSS光场 $|\Psi(4)(f_j)\rangle_q$ 处于等次幂 N_j 次方振幅最小测不准态；

2）如果 $\sum_{j=1}^{q}|f_j^{(K)}(x,y,z)|^{N_j}e^{N_j\alpha^{(K)}z}\neq\sum_{j=1}^{q}|\,|f_j^{(L)}(x,y,z)|^{N_j}e^{N_j\alpha^{(L)}z}$，并且态间的初始相位差以及各单模相

干态光场的光子干涉项之和满足条件:$\{(\theta_K-\theta_L)+\sum_{j=1}^{q}|f_j^{(K)}(x,y,z)f_j^{(L)}(x,y,z)|e^{(\alpha^{(K)}+\alpha^{(L)})z}\sin(\Phi_j^{(K)}(x,y,z)-\Phi_j^{(L)}(x,y,z))\}\in[\pm2k\pi-\frac{\pi}{2},\pm2k\pi+\frac{\pi}{2}](k=0,1,\cdots)$ 时,$Y_M<0$。即4MFSS光场 $|\Psi(4)(f_j)\rangle_q$ 的广义磁场分量呈现出周期性变化的不等幂次 N_j 次方振幅压缩效应。

3.2 $n^{(K)}$ 与 $n^{(L)}$ 一个取偶数另一个取奇数时的情况

如果态间的初始相位差以及各单模相干态光场的光子干涉项之和满足条件 $\{(\theta_K-\theta_L)+\sum_{j=1}^{q}|f_j^{(K)}(x,y,z)f_j^{(L)}(x,y,z)|e^{(\alpha^{(K)}+\alpha^{(L)})z}\sin(\Phi_j^{(K)}(x,y,z)-\Phi_j^{(L)}(x,y,z))\}\in[\pm2k\pi-\frac{\pi}{2},\pm2k\pi+\frac{\pi}{2}](k=0,1,\cdots)$ 时,$Y_H<0$。即在上述条件下,4MFSS光场 $|\Psi(4)(f_j)\rangle_q$ 的广义磁场分量呈现出周期性变化的不等幂次 N_j 次方振幅压缩效应。

4　介质对4MFSS光场 $|\Psi^{(4)}(f_j)\rangle_q$ 压缩效应的影响

对于4MFSS光场 $|\Psi^{(4)}(f_j)\rangle_q$,光子数表达式为:$\langle N_j^{(K)}\rangle_q^4=\sum_{K=1}^{4}\{\sum_{j=1}^{q}|f_j^{(K)}(x,y,z)|^2e^{2\alpha^{(K)}z}$,表示4MFSS光场 $|\Psi^{(4)}(f_j)\rangle_q$ 的平均光子数之和。

在增益介质中,增益系数大于零即 $\alpha^{(K)}>0$,随着4MFSS光场 $|\Psi^{(4)}(f_j)\rangle_q$ 在介质中传播距离的增大,光场的平均光子数以及总光子数增加,光场强度增加,从而导致4MFSS光场 $|\Psi^{(4)}(f_j)\rangle_q$ 的压缩幅度增大、压缩效应增强。对于吸收介质,吸收系数小于零即 $\alpha^{(K)}<0$,随着4MFSS光场 $|\Psi^{(4)}(f_j)\rangle_q$ 在介质中传播距离的增大,光场的平均光子数以及总光子数减少,光场强度减小,从而导致4MFSS光场 $|\Psi^{(4)}(f_j)\rangle_q$ 的压缩幅度减小、压缩效应减弱。

5　结论

综上所述,可得以下结论:

①在一些特定的条件下,介质中4MFSS光场广义磁场分量可呈现出周期性变化的不等幂次 N_j 次方高次振幅压缩效应;②介质中4MFSS光场广义磁场分量所呈现的 N_j 次方高次振幅效应的压缩幅度,明显受到介质的增益系数或吸收系数的直接影响。对于增益介质而言,随着传播距离的增大,光场 N_j 次方高次振幅压缩现象的压缩幅度增大、压缩效应增强。对于吸收介质而言,随着光场传播距离的增大,光场 N_j 次方高次振幅压缩现象的压缩幅度减小、压缩效应减弱。

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The N_j - th Power Amplitude - squeezing of Generalized Magnetic - field of 4MFSS Light Field in Medium

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Abstract: Based on the state superposition principle of quantum mechanics, asymmetrical multimode functional superposition state light field with the superposition of four quantum states is constructed. By using multimode squeezing state theory, this paper makes a detailed study of the unequal - power higher - power amplitude - squeezing of generalized magnetic - field of 4MFSS light field in medium and it is found that 1) under certain conditions, the generalized magnetic - field of 4MFSS light field shows periodical generalized nonlinear unequal - power higher - power amplitude - squeezing; 2) the N_j - th power higher - power amplitude - squeezing shown in the generalized magnetic - field of 4MFSS light field is obviously affected by the coefficient of the gain medium or of the absorption medium. In the gain medium, when the light field spreading distance becomes farther, the extent, range and effect of N_j - th power higher - power amplitude - squeezing are intensified; in the absorption medium, when the light field spreading distance becomes farther, the extent, range and effect of N_j - th power higher - power amplitude - squeezing are decreased.

Key words: 4MFSS light field; gain medium; absorption medium; generalized magnetic - field; multimode functional superposition state; unequal - power amplitude - squeezing