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基于 3D-VTGM-SBPM 平行定向耦合器模拟研究

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摘　要　提出基于变量变换伽辽金法的三维半矢量束传播法(3D-VTGM-SBPM)，可直接应用于三维光波导器件的光波传输模拟．采用适当的变量变换，将三维半矢量 BPM 基本方程归结为一阶常微分方程组，避免了非物理反射且能反映模场的偏振特性，成功的分析了基于脊形光波导的平行定向耦合器的光波传输特性．

关键词　光波导器件；变量变换伽辽金法；三维束传播法；半矢量；平行定向耦合器

中图分类号　TN25　　　**文献标识码**　A

0　引言

光通信的迅猛发展推动了市场对光波导器件的需求，基于脊形光波导的平行定向耦合器是组建全光网的(AON)的重要器件，模拟分析其光波传输特性有助于优化其结构．束传输法(BPM)是一种灵活且具有良好拓展性的技术，已成为光波导数值分析的主要方法[1]，且已经出现了有限元法 BPM[2] 和有限差分法 BPM[3] 等常用数值计算方法．但这些方法往往方程繁杂，且要处理复杂的边界问题[4]．伽辽金法(GM)[5,6] 将电场或磁场展开成一组正交完备的基函数的叠加，其矩阵为对称型矩阵，计算效率较高．变量变换伽辽金法(VTGM)[7] 通过适当的正切(余切)函数变换，将无限平面映射成为单位平面，使该单位平面边界上的电磁场自然为零，避免了边界截断，提高了计算准确度．近年来，GM 和 VTGM 被广泛用于求解光波导本征值[8,9] 问题，但基于 VTGM 的束传输法多采用二维形式，基于 VTGM 的三维束传输法(BPM)仅有少量文献报道，且只有标量形式[10]．本文提出基于变量变换伽辽金法的三维半矢量束传播法(3D-VTGM-SBPM)，将三维 BPM 基本方程归结为一阶常微分方程组，可直接模拟三维光波导器件的光波传输模拟，且能反映模场的偏振特性，是模拟分析光波导器件的较好方法．

1　3D-VTGM-SBPM

在慢变包络近似下，由麦克斯韦方程组可得光纤和光波导中单色光的三维半矢量 BPM 基本方程

$$2\mathrm{j}k_0\,\bar{n}\frac{\partial E_x}{\partial z}=\frac{\partial^2 E_x}{\partial x^2}+\frac{\partial^2 E_x}{\partial y^2}+k_0^2(n^2-\bar{n}^2)E_x+\frac{\partial}{\partial x}\left[E_x\,\frac{\partial \ln(n^2)}{\partial x}\right]\tag{1}$$

$$2\mathrm{j}k_0\,\bar{n}\frac{\partial E_y}{\partial z}=\frac{\partial^2 E_y}{\partial x^2}+\frac{\partial^2 E_y}{\partial y^2}+k_0^2(n^2-\bar{n}^2)E_y+\frac{\partial}{\partial y}\left[E_y\,\frac{\partial \ln(n^2)}{\partial y}\right]\tag{2}$$

式中，$\bar{n}$称为参考折射率，引入如下变量变换

$$x=\sigma_x\tan\left[\pi(u-1/2)\right]\tag{3}$$

$$y=\sigma_y\tan\left[\pi(v-1/2)\right]\tag{4}$$

则将无限大平面映射成为单位平面，式(1)和(2)分别变为

$$2\mathrm{j}\,\bar{n}k_0\,\frac{\partial E_x}{\partial z}=\left(\frac{\mathrm{d}u}{\mathrm{d}x}\right)^2\cdot\frac{\partial^2 E_x}{\partial u^2}+\frac{\mathrm{d}^2u}{\mathrm{d}x^2}\cdot\frac{\partial E_x}{\partial u}+\left(\frac{\mathrm{d}v}{\mathrm{d}y}\right)^2\cdot\frac{\partial^2 E_x}{\partial v^2}+\frac{\mathrm{d}^2v}{\mathrm{d}y^2}\cdot\frac{\partial E_x}{\partial v}+k_0^2(n^2-\bar{n}^2)E_x+2\left(\frac{\mathrm{d}u}{\mathrm{d}x}\right)^2\cdot\frac{\partial}{\partial u}\left(E_x\,\frac{\partial\ln(n)}{\partial u}\right)+2\,\frac{\mathrm{d}^2u}{\mathrm{d}x^2}E_x\,\frac{\partial\ln(n)}{\partial u}\tag{5}$$

$$2\mathrm{j}\,\bar{n}k_0\,\frac{\partial E_y}{\partial z}=\left(\frac{\mathrm{d}u}{\mathrm{d}x}\right)^2\cdot\frac{\partial^2 E_y}{\partial u^2}+\frac{\mathrm{d}^2u}{\mathrm{d}x^2}\cdot\frac{\partial E_y}{\partial u}+\left(\frac{\mathrm{d}v}{\mathrm{d}y}\right)^2\cdot\frac{\partial^2 E_y}{\partial v^2}+\frac{\mathrm{d}^2v}{\mathrm{d}y^2}\cdot\frac{\partial E_y}{\partial v}+k_0^2(n^2-\bar{n}^2)E_y+2\left(\frac{\mathrm{d}v}{\mathrm{d}y}\right)^2\cdot\frac{\partial}{\partial v}\left(E_y\,\frac{\partial\ln(n)}{\partial v}\right)+2\,\frac{\mathrm{d}^2v}{\mathrm{d}y^2}E_y\,\frac{\partial\ln(n)}{\partial v}\tag{6}$$

通过变换，边界上的电磁场自然为零，避免了非物理反射．将电场在有限区间 $0\leqslant u\leqslant 1$，$0\leqslant v\leqslant 1$ 展开成正弦级数，且为正交完全集，即

$$E_x=\sum_{k=1}^{N}C_k^x\Psi_k(u,v)=\sum_{p=1}^{N_x}\sum_{q=1}^{N_y}C_{pq}^x\Psi_{pq}(u,v)\tag{7}$$

$$E_y=\sum_{k=1}^{N}C_k^y\Psi_k(u,v)=\sum_{p=1}^{N_x}\sum_{q=1}^{N_y}C_{pq}^y\Psi_{pq}(u,v)\tag{8}$$

其中基函数为

$$\Psi_{pq}=\sqrt{2}\sin(p\pi u)\cdot\sqrt{2}\sin(q\pi v)=2\sin(p\pi u)\cdot\sin(q\pi v)\tag{9}$$

N_x，N_y 分别为 u，v 方向的级数项数．p，q 分别由式(10)、(11)决定

$$p=1+(k-1)\,\mathrm{div}N_y\tag{10}$$

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$$q=1+(k-1)\mathrm{mod}N_y \qquad (11)$$

其中 div 和 mod 分别表示取整和求余．将式(7)和(8)代入式(5)和(6)，并应用迦辽金法，得

$$\mathrm{j}\sum_{p=1}^{N_x}\sum_{q=1}^{N_y}R^x_{p'q'pq}\cdot\frac{\mathrm{d}C^x_{pq}}{\mathrm{d}z}=\sum_{p=1}^{N_x}\sum_{q=1}^{N_x}S^x_{p'q'pq}\cdot C^x_{pq} \qquad (12)$$

$$\mathrm{j}\sum_{p=1}^{N_x}\sum_{q=1}^{N_y}R^y_{p'q'pq}\cdot\frac{\mathrm{d}C^y_{pq}}{\mathrm{d}z}=\sum_{p=1}^{N_x}\sum_{q=1}^{N_x}S^y_{p'q'pq}\cdot C^y_{pq} \qquad (13)$$

写成矩阵形式为

$$S^xC^x=R^x\frac{\mathrm{d}C^x}{\mathrm{d}z} \qquad (14)$$

$$S^yC^y=R^y\frac{\mathrm{d}C^y}{\mathrm{d}z} \qquad (15)$$

其中的矩阵元由式(16)～(19)确定

$$S^x_{p'q'pq}=\sum_{i=1}^{4}I_i+k_0^2\int_0^1\int_0^1\Psi_{p'q'}n^2(u,v,z)\Psi_{pq}\mathrm{d}u\mathrm{d}v+I_5+I_6-k_0^2\,\bar{n}^2\delta_{p'p}\delta_{q'q} \qquad (16)$$

$$R^x_{p'q'pq}=2\mathrm{j}k_0\,\bar{n}\int_0^1\int_0^1\Psi_{p'q'}\Psi_{pq}\mathrm{d}u\mathrm{d}v=2\mathrm{j}k_0\,\bar{n}\delta_{p'p}\delta_{q'q} \qquad (17)$$

$$S^y_{p'q'pq}=\sum_{i=1}^{4}I_i+k_0^2\int_0^1\int_0^1\Psi_{p'q'}n^2(u,v,z)\Psi_{pq}\mathrm{d}u\mathrm{d}v+I_7+I_8-k_0^2\,\bar{n}^2\delta_{p'p}\delta_{q'q} \qquad (18)$$

$$R^y_{p'q'pq}=2\mathrm{j}k_0\,\bar{n}\int_0^1\int_0^1\Psi_{p'q'}\Psi_{pq}\mathrm{d}u\mathrm{d}v=2\mathrm{j}k_0\,\bar{n}\delta_{p'p}\delta_{q'q} \qquad (19)$$

式中 $I_m(m=1\sim8)$ 为 8 个二重积分，可参考文献[7]写出其解析表达式．式(14)和式(15)是一组常微分方程，在给定 $E(x,y,z=0)$ 后，便可以求出 $z>0$ 区域的电场分布．另外，如令式(14)和式(15)中的 d/dz=0，则可直接约化为本征值方程，用于求解本征值问题．

2　数值结果与讨论

利用上述方法对图 1 的平行定向耦合器进行分析和模拟，其参量分别为：$\omega=3$ μm，$d=1$ μm，$n_c=1$，$n_f=3.44$，$n_s=3.36$，$h=1$ μm，$t=0.9$ μm，$\lambda=1.55$ μm. 为使式(14)和式(15)快速收敛，并保证场形不弯曲变形，参照文献[7,9]选取 $\sigma_x=\omega+d/2$，$\sigma_y=h/2$.

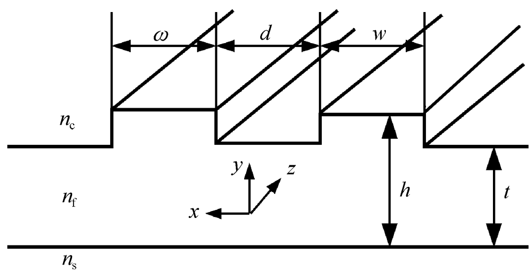

图 1　基于脊形光波导的平行对称定向耦合器

Fig. 1　Parallel symmetrical directional coupler based on optical rib waveguides

图 2 给出定向耦合器承载的电场 TE 波的偶模和奇模的模场分布；图3给出定向耦合器承载的电

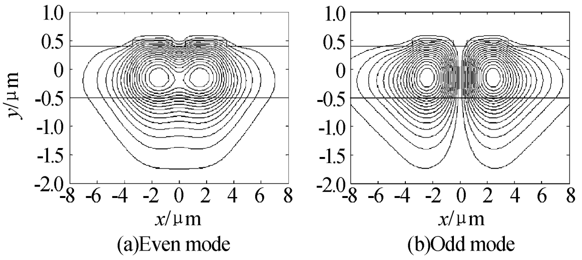

图 2　定向耦合器承载的电场 TE 模分布

Fig. 2　Electric TE mode field distributions supported by the directional coupler

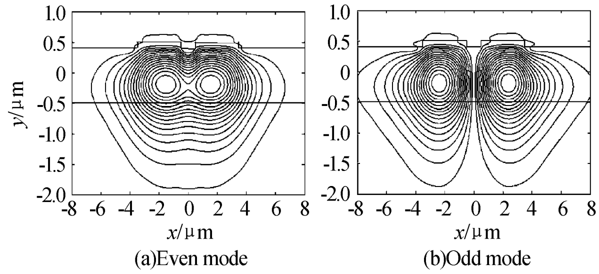

图 3　定向耦合器承载的电场 TM 模分布

Fig. 3　Electric TM mode field distributions supported by the directional coupler

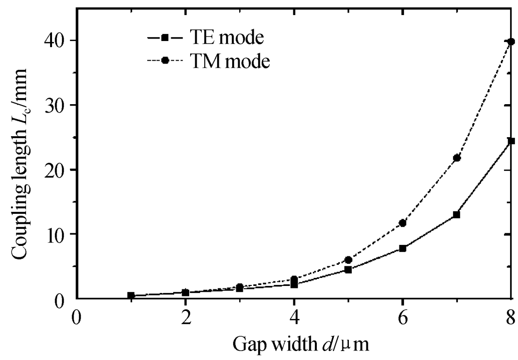

图 4　1.55 μm 的光波在定向耦合器中传输时耦合长度随波导间距的变化

Fig. 4　Coupling length as a function of the gap width at a wavelength of 1.55 μm for the directional coupler

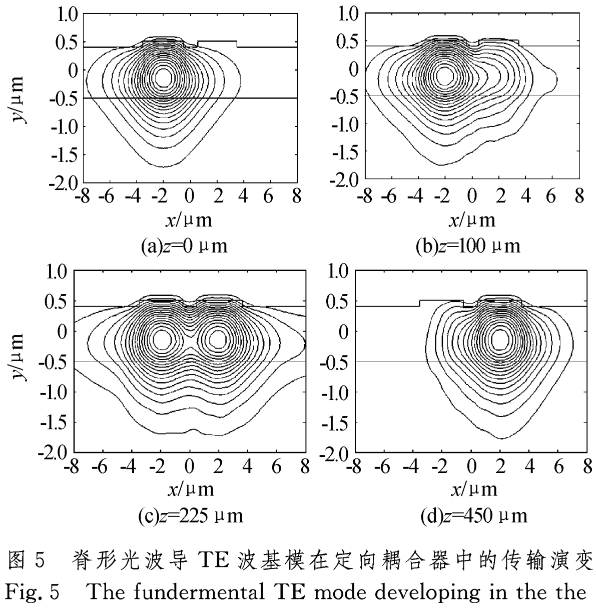

图 5　脊形光波导 TE 波基模在定向耦合器中的传输演变

Fig. 5　The fundermental TE mode developing in the the directional coupler

场TM波偶模和奇模的模场分布．在图3中看到了TM模的畸变，证明半矢量方法更能反映物理实质．图4是耦合长度L_c随耦合波导间距d的变化关系，由图中可以看出，L_c随波导间距增大近似指数增长，这和文献[11]的结果吻合较好．用左通道中的电场TE波基模进行激励，得到它在定向耦合器中传输演变情况如图5．在$z=450$ μm处实现了交叉态，说明其耦合长度为450 μm，和文献[10,11]的结果吻合较好．TM波在定向耦合器中的传输演变情况与此类似．

3 结论

本文提出了基于VTGM的三维半矢量束传播法（3D-VTGM-SBPM）的数理模型，用以模拟分析基于脊形光波导的平行定向耦合器的光波传输特性．对比了定向耦合器承载的电场TE波和TM波的偶模和奇模的模场分布，看到了TM模的畸变，证明半矢量方法更能反映物理实质．用TE波基模进行激励，传输450 μm出现交叉态，所得结果和其他已发表的结果非常接近．3D-VTGM-SBPM将光波传输问题归结为一阶常微分方程组，导出矩阵小，计算效率高，将无限域问题转换成有限域问题，避免了非物理反射，提高了计算准确度，还可直接约化为本征值方程用于求解本征值问题．因采用半矢量方法，既能反映光场的偏振特性，又具有和标量方法相当的计算效率，非常适合于分析光波导器件．

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Analysis of Parallel Directional Coupler Using 3D-Semi-vectorial BPM Based on the Variable Transformed Galerkin Method

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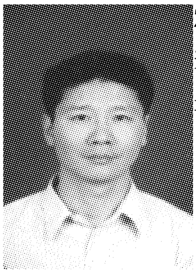
Abstract　A novel three-dimensional semi-vectorial beam propagation method based on the variable transformed galerkin method(3D-VTGM-SBPM) is proposed for directly modeling optical waveguides, and is successfully applied to simulate parallel directional coupler. By adopting proper variable transformation, the basic three-dimensional semi-vectorial BPM equations is reduced to a first-order normal differential equation system. The artificial boundary condition is avoided, and the polarization characteristic of the mode field is displayed.

Keywords　Optical waveguide devices; Variable transformed galerkin method(VTGM); Three-dimensional beam propagation method(3D-BPM); Semi-vector; Parallel directional coupler



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