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Y型光子晶体偏振光分束器

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摘要:基于偏振模式不同的光波在二维光子晶体中的传播特性不同,设计出一个支路半径相同的Y型二维光子晶体偏振光分束器.通过时域有限差分法对该分束器进行数值计算与模拟分析.结果表明,该分束器能够实现TE模和TM模平行、高效分束.当波长为1.55 μm的高斯脉冲入射时,TE模透射率可达97%,TM模透射率可达93.5%,且该结构尺寸仅有6.3 μm×6.8 μm.这些特性使其在未来的集成光路中具有很好的应用前景.

关 键 词:光子晶体;偏振光分束器;时域有限差分法
中图分类号:O734 **文献标识码**:A

Polarization beam splitter for Y type photonic crystal

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Abstract: The design and simulation of polarization beam splitter (PBS) for Y type two-dimensional photonic crystal with the same beam splitting radius are presented. It is based on the different properties of the light waves with different polarization modes propagating in the two-dimensional photonic crystal. The function of the PBS were numerically simulated and analyzed using the finite difference time domain (FDTD) method. It is shown that parallel splitting with high efficiency for TE and TM modes can be achieved. The transmission probability can reach over 97% for TE mode and over 93.5% for TM mode for a Gaussian pulse light with a wavelength of 1.55 μm. The size of the splitter is only 6.3 μm × 6.8 μm. Owing to these excellent features, the PBS is a promising candidate in the future photonic integrated circuits.

Key words: photonic crystal, polarization beam splitter, finite difference time domain
PACS: 42.70.Qs, 78.67.Pt, 13.88.+e, 47.11.Bc

引言

自1987年Yablonovitch[1]和John[2]提出光子晶体概念以来,基于光子晶体对光波的可控性[3]引起学术界的广泛关注.光子晶体是一种介电常数不同的材料在空间呈周期性排列形成的结构,其主要特征是光子禁带[4-5]和光子局域,利用其特性可设计多种光电子元件,如波分复用/解复用器[6]、光滤波器[7]、光开关[8]和光子晶体偏振光分束器[9-10]等.

偏振光分束器是集成光路的重要组成部分,它能将两两相互正交的偏振模式光波分开,并使其沿不同方向传播.传统偏振光分束器是利用天然晶体的双折射效应或者多层膜结构的偏振选择性来实现光的分束.天然晶体对厚度要求高,而多层膜结构加工工艺复杂,因此传统偏振光分束器在尺寸上无法满足光集成的条件,从而限制了其在微电子领域的发展.

光子晶体器件由于具有光控性好、尺寸小等特

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性而备受人们关注. 近年来,已经研究出多种类型的光子晶体分束器[11-13],其主要原理是利用两种偏振光在光子晶体中不同特性来实现光束分束. 主要有三种类型:1)利用光子晶体缺陷波导导模的不同耦合特性来实现偏振光分束[13];2)利用两种偏振模式在光子晶体中正、负折射差异来实现偏振光分束[14-16];3)利用两种偏振模式带隙不同来实现偏振光分束[17]. 第 1 类光子晶体偏振光分束器需要引入多列波导,降低了透射效率;第 2、3 类光子晶体偏振光分束器需要引入波导导光. 光子晶体线性腔一个重要的应用就是可以用于导光,本文利用光子晶体线性腔实现导光.

为克服引入多列光子晶体波导、引入波导导光和光子晶体偏振光分束器尺寸大的缺点,基于光子晶体波导与偏振模式不同的带隙理论,设计出一个支路半径相同的 Y 型光子晶体波导偏振光分束器,通过数值计算与模拟分析表明,该分束器能实现 TE 模与 TM 模的分束,且有效率高、尺寸小等特点. 在未来集成光路中有重要的应用价值.

1　数值算法

研究光子晶体的计算方法有很多种,如平面波展开法[17-18]、格林函数方法[19-20]、传输矩阵法[21]、多重散射法[22]和时域有限差分(FDTD)法[23-24]. 本文通过 FDTD 法研究光子晶体的特性. FDTD 是对 Maxwell 方程进行离散化处理,将方程中两个旋度关于空间变量和时间变量偏微分方程转化为差分方程,从而转换为离散网格节点上的时域有限差分方程.

Maxwell 方程为:

$$\nabla \times H = \varepsilon \frac{\partial E}{\partial t} + \sigma E \quad , \quad (1)$$

$$\nabla \times E = -\mu \frac{\partial H}{\partial t} - \xi H \quad , \quad (2)$$

其中 ε 为介质介电常数,μ 为磁导系数,σ 为电导率,ξ 为导磁率. 在光子晶体结构中,电磁波的传播与 Z 向无关($K_z=0$),电磁波分解为 TE 模(电磁分量为 $E=(E_x,E_y,0)$,$H=(0,0,H_z)$)和 TM 模(电磁分量 $E=(0,0,E_z)$,$H(H_x,H_y,0)$)两种偏振模式,此时 Maxwell 方程可转换为:

TE 模式:

$$E_x^{n+1}(i+\frac{1}{2},j) = C_n(i+\frac{1}{2},j)[-D_n(i+\frac{1}{2},j) + \frac{H_z^{n+\frac{1}{2}}(i+\frac{1}{2},j+\frac{1}{2}) - H_z^{n+\frac{1}{2}}(i+\frac{1}{2},j-\frac{1}{2})}{\Delta y}] \quad , \quad (3)$$

$$E_y^{n+1}(i,j+\frac{1}{2}) = C_n(i,j+\frac{1}{2})[-D_n(i,j+\frac{1}{2})E_y^n(i,J+\frac{1}{2}) + \frac{H_z^{n+\frac{1}{2}}(i+\frac{1}{2},j+\frac{1}{2}) - H_z^{n+\frac{1}{2}}(i-\frac{1}{2},j-\frac{1}{2})}{\Delta x}] \quad , (4)$$

$$H_z^{n+\frac{1}{2}}(i+\frac{1}{2},j+\frac{1}{2}) = C'_n(i+\frac{1}{2},j+\frac{1}{2})[-D'_n(i+\frac{1}{2},j+\frac{1}{2})H_z^{n-\frac{1}{2}}(i+\frac{1}{2},j+\frac{1}{2}) + \frac{E_x^n(i+\frac{1}{2},j+1) - E_x^n(i+\frac{1}{2},j)}{\Delta y} - \frac{E_y^n(i+1,j+\frac{1}{2}) - E_y^n(i,j+\frac{1}{2})}{\Delta x}] \quad . \quad (5)$$

TM 模式:

$$H_x^{n+\frac{1}{2}}(i,j+\frac{1}{2}) = C'_n(i,j+\frac{1}{2})[-D'_n(i,j+\frac{1}{2})H_x^{n-\frac{1}{2}}(i,j+\frac{1}{2}) - \frac{E_z^n(i,j+1) - E_z^n(i,j)}{\Delta y}] \quad , \quad (6)$$

$$H_y^{n+\frac{1}{2}}(i+\frac{1}{2},j) = C'_n(i+\frac{1}{2},j)[-D'_n(i+\frac{1}{2},j)H_y^{n-\frac{1}{2}}(i+\frac{1}{2},j) + \frac{E_z^n(i+1,j) - E_z^n(i,j)}{\Delta x}] \quad , \quad (7)$$

$$E_z^{n+1}(i,j) = C_n(i,j)[-D_n(i,j)E_z^n(i,j) + \frac{H_y^{n+\frac{1}{2}}(i+\frac{1}{2},j) - H_y^{n+\frac{1}{2}}(i-\frac{1}{2},j)}{\Delta x} - \frac{H_x^{n+\frac{1}{2}}(i,j+\frac{1}{2}) - H_x^{n+\frac{1}{2}}(i,j-\frac{1}{2})}{\Delta y}] \quad . \quad (8)$$

其中 C_n、C'_n、D_n、D'_n 等参量的具体形式为:

$$C_n = \left\{\sqrt{\frac{\mu_0}{\varepsilon_0}}\left[\frac{\delta_n(i,j)}{2} + \frac{\varepsilon_n(i,j)}{\Delta t}\right]\right\}^{-1} \quad , \quad (9)$$

$$D_n = \left\{\sqrt{\frac{\mu_0}{\varepsilon_0}}\left[\frac{\delta_n(i,j)}{2} - \frac{\varepsilon_n(i,j)}{\Delta t}\right]\right\} \quad , \quad (10)$$

$$C'_n = \left\{\sqrt{\frac{\mu_0}{\varepsilon_0}}\left[\frac{\xi_n(i,j)}{2} + \frac{\mu_n(i,j)}{\Delta t}\right]\right\}^{-1} \quad , \quad (11)$$

$$D'_n = \left\{\sqrt{\frac{\mu_0}{\varepsilon_0}}\left[\frac{\xi_n(i,j)}{2} - \frac{\mu_n(i,j)}{\Delta t}\right]\right\} \quad . \quad (12)$$

为了在迭代计算收敛过程得到稳定解,时间步长必须满足:

$$\Delta t \leqslant \frac{1}{c_p\sqrt{\Delta x^{-2} + \Delta y^{-2}}} \quad , \quad (13)$$

其中,c_p 为空间光波的最大相速. 网格越密,即 Δx,Δy,Δt 越小,所得计算精度越高.

2　偏振光分束器的设计与分析

选取介电常数为 18.5 的锗材料为背景材料,在

其上引入不同结构的空气孔.当空气孔在锗基底上成三角晶格分布时,结构简图如图1(a)所示,晶格常数为α,其能带如图1(b)所示.从图1(b)中发现:在空气孔半径为0.8α,归一化频率$\alpha/\lambda=0.473\sim0.484$,TE模为禁带,TM模为导带;当空气孔半径为$0.98\alpha$,归一化频率$\alpha/\lambda=0.428\sim0.513$,TE模和TM模均为禁带.当空气孔在锗基底上成正方晶格分布时,结构简图如图2(a)所示,Z轴方向相邻两个空气孔中心位置距离为0.8α,X轴方向相邻空气孔中心距离为α,图2(b)所示为正方晶格光子晶体禁带图,从图2(b)中发现:在空气孔半径为0.8α,归一化频率$\alpha/\lambda=0.471\sim0.487$,TM模为禁带,TE模为导带.比较图1(b)和图2(b)发现,当空气孔半径为0.8α时,在相同的归一化频率范围$\alpha/\lambda=0.473\sim0.484$内,三角晶格光子晶体对于TE模光波为禁带,TM模光波为导带;正方晶格光子晶体对于TM模光波为禁带,TE模光波为导带.当空气孔半径为0.98α时,三角晶格光子晶体对于TE模和TM模光波均为禁带.若将空气孔半径为0.8α的三角晶格和正方晶体光子晶体置于空气孔半径为0.98α的三角晶格光子晶体波导中有可能实现TE模和TM模光波分束.

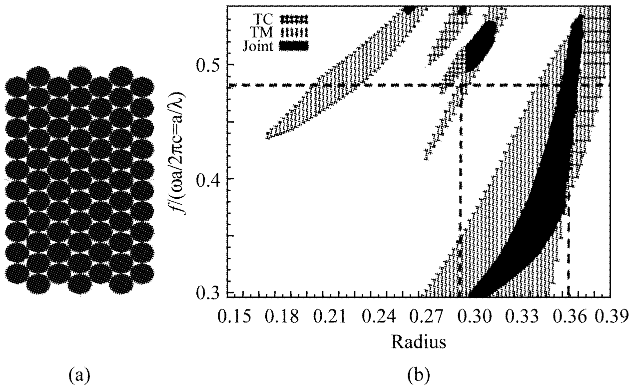

图1 三角晶格结构及其能带图(a)三角晶格光子晶体结构,(b)三角晶格归一化频率随空气孔半径的变化,纵格表示TE模禁带,竖纹表示TM模禁带,黑色表示TE模与TM模共同的禁带

Fig. 1 The structure and bandgap of triangular lattice photonic crystal (a) The structure of triangular lattice photonic crystal, (b) The dependence of the normalized frequency on the hole radius. Gray shows the bandgap for TE mode, cross for TM mode, black for both of them

在空气孔半径为0.989α的三角光子晶体中引入光子晶体波导C,如图3(a)所示,TE模和TM模光波在光子晶体波导中实现低损耗传输[25].为实现TE模和TM模同时分离,在传输路径两个支路上引

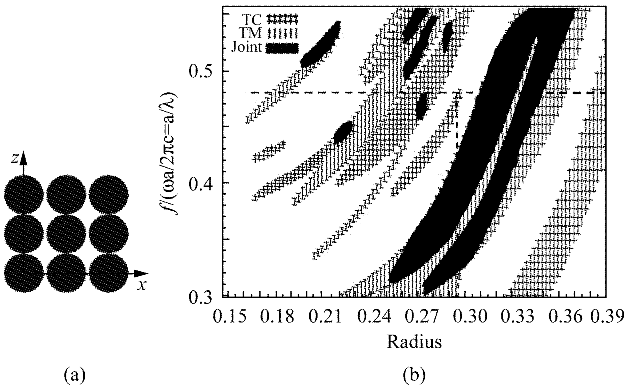

图2 正方晶格结构及其能带图(a)正方晶格光子晶体结构(b)正方晶格归一化频率随空气孔半径的变化,纵格表示TE模禁带,竖纹表示TM模禁带,黑色表示TE模与TM模共同的禁带

Fig. 2 The bandgap of square lattice photonic crystal (a) The structure of square lattice photonic, (b) The dependence of the normalized frequency on the hole radius. Gray shows bandgap for TE mode, cross for TM mode, black for both of them

入分束结构A和B,形成一个二维光子晶体偏振光分束器结构,如图3(b)所示,其中A为图2(a)所示的正方光子晶体结构,B为图1(a)所示的三角光子晶体结构.选取归一化频率$\alpha/\lambda=0.483$作为工作频率,入射波长为1.55 μm、宽度为0.3 μm的高斯脉冲垂直入射.取分束结构A、B的空气孔半径为0.8α,其他空气孔半径为0.98α,根据能带图分析,TE模只能从结构A透射,TM模只能从结构B透射,从而实现了TE模与TM模平行、高效分束.该光子晶体偏振光分束器结构由横向13个×纵向14个光子晶体单元层组成,其尺寸为6.3 μm×6.8 μm.

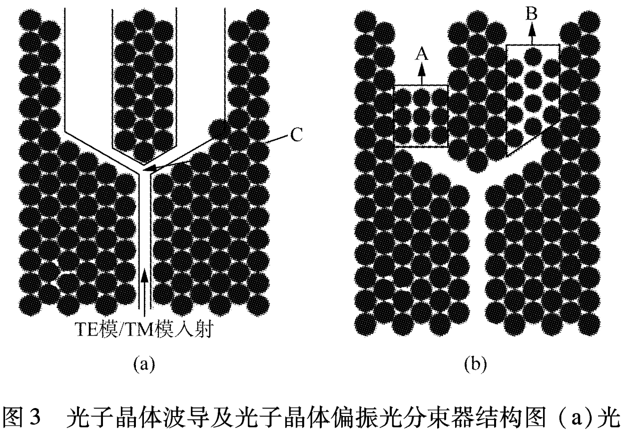

图3 光子晶体波导及光子晶体偏振光分束器结构图(a)光子晶体波导,(b)二维光子晶体偏振光分束器结构

Fig. 3 The structures of the photonic crystal waveguide (a) and two-dimensional photonic crystal beam splitter (b)

进一步通过FDTD方法数值计算与模拟TE模和TM模在该光子晶体分束结构中的传播特性.图4

给出了此光子晶体偏振光分束器在归一化频率 $\alpha/\lambda=0.483$ 处,光场达到稳定时电场强度分布图,由图 4(a)可知,TE 模只从分束结构 A 透射;由图 4(b)可知,TM 模只从分束结构 B 透射,实现了 TE 模与 TM 模的平行分离.

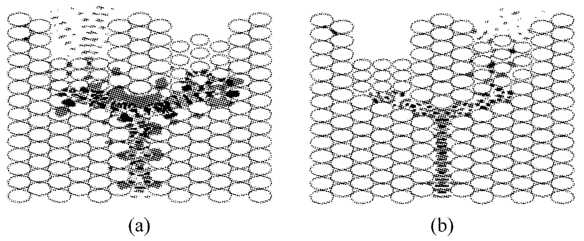

图 4 归一化频率 $\alpha/\lambda=0.483$ 处,光场达到稳定时,电场强度分布图 (a)TE 模,(b)TM 模
Fig. 4 The distribution of electromagnetic field for TE mode (a) and TM mode (b) when $\alpha/\lambda=0.483$

还研究了该光子晶体偏振光分束器的透射效率,如图 5 所示,其中虚线表示 TE 模的透射率,实线表示 TM 模的透射率. 由图 5 可知,波长在 1.51 ~ 1.568 μm 范围内,TE 模和 TM 模透射率均高于 90%,在入射波长为 1.55 μm 时,TE 模透射率可达 97.1%,TM 模透射率可达 93.5%,实现了 TE 模和 TM 模光波的的高效分离.

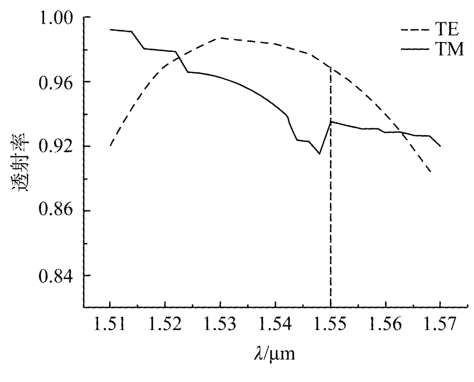

图 5 二维光子晶体波导偏振光分束器结构中 TE 模和 TM 的模透射率与波长的关系
Fig. 5 The relation between electromagnetic wave transmission probability and incident wavelength in 2-D photonic crystal polarization beam splitter

3 结论

采用 FDTD 法数值计算与模拟分析了三角晶格和正方晶格光子晶体的能带结构,讨论了其在偏振器方面的应用. 结果表明,该结构对于入射波长为 1.55 μm 的光波,能实现 TE 模和 TM 模光波的平行、高效分束. 与传统的偏振光分束器相比,该偏振光分束器具分束效率高、尺寸小等优点,在未来的集成光路中有较高的实际应用价值.

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