第 43 卷 第 16 期/2023 年 8 月/光学学报 内封面文章·特邀综述

光学学报

微纳光学中的光子自旋霍尔效应

冯娟[1]，王波[1*]，陈险峰[1,2,3]

[1]区域光纤通信网与新型光通信系统国家重点实验室，上海交通大学物理与天文学院，上海 200240；

[2]上海量子科学研究中心，上海 201315；

[3]山东师范大学光场调控及应用中心，山东 济南 250358

摘要 光的自旋轨道耦合现象在微纳尺度的光与物质相互作用中几乎无处不在。偶极辐射等非傍轴光在空间传播中具有自发自旋轨道耦合，当光遇到各向异性结构、磁性结构、手性结构，以及具有波长尺度空间不均匀的结构时，自旋轨道耦合现象也时常发生。对光的自旋深入研究不仅有利于新光学现象的发掘，还为微纳光场操纵提供了新途径。近些年来，基于几何相位的超构表面在新型自旋光控制中展示出了很多重要应用，实现了多维度、多波长的激光自旋控制，产生了纠缠光子、自旋依赖的偏振热光源等，也发展了一些基于光自旋的超灵敏测量手段。相比而言，光与无序微纳结构相互作用的研究则较少。无序结构内在的随机性使得该体系的自旋轨道耦合变得复杂，光场的表征需要考虑统计特性，为测量、分析带来了一定挑战。此外，随机系统的光子自旋霍尔效应机理还没有完全清楚，随机几何相位涨落或者涡旋都能使光产生自旋霍尔效应，但是两者有很大的物理差异。因此，光子自旋霍尔效应与无序几何相位之间的规律还有待深入探索。首先介绍光的自旋概念、不同体系下的基本自旋轨道耦合现象，然后分析以超构表面为平台研究的二维随机体系对光自旋轨道耦合与光子自旋霍尔效应的影响，包括各向异性无序、磁光涨落、涡旋、随机偶极子辐射等产生的光自旋分离现象。这些研究和分析有利于将来用光自旋霍尔信号作为新的探测和控制手段，研究相互作用体系的相变与演化。

关键词 光自旋；超构表面；随机现象；光学涡旋；几何相位

中图分类号 O436 **文献标志码** A **DOI**: 10.3788/AOS230895

1 引 言

1.1 自旋：施特恩-格拉赫实验

施特恩-格拉赫（Stern-Gerlach）实验由德国物理学家施特恩和格拉赫在1922年完成[1]。在实验中，他们将一束银原子通过具有空间梯度的磁场区域，并记录原子的散射情况。实验结果显示，银原子在屏幕上集中于两个位置，而非之前所推测的连续区域。这表明原子中存在两个具有离散数值的电子角动量。在随后的一段时间里，人们逐渐意识到，Stern-Gerlach实验中所观察到的磁矩来自于电子的内禀角动量，称之为自旋角动量（spin）。自旋角动量不同于轨道角动量，它与电子的空间坐标无关，并且在任意方向都只能投影两个本征态，本征值分别为$\pm\hbar/2$（$\hbar$为简约普朗克常数）。自旋是现代物理中十分核心的概念：整数、半整数的自旋决定了粒子不同的统计特性（费米-狄拉克或者玻色-爱因斯坦统计）；原子的自旋轨道耦合会导致光谱的精细结构；在凝聚态领域，相对论的自旋轨道耦合可以产生自旋霍尔效应，并由此发展出了自旋电子学。自旋不仅是粒子性的体现，也存在于矢量波动体系中。如今，自旋概念已经衍生到了物理学的很多分支，尤其是在电磁波、机械波中得到了实验证明，并带来了很多新的效应与应用。

1.2 光自旋的定义与基本特点

光子是玻色子，具有整数自旋。从经典电磁波的角度来看，自旋描述了电磁场的内禀角动量，代表光的偏振状态。根据SO(3)矢量旋转操作，可以获得光子的自旋角动量算符$\hat{S}=[\hat{S}_x,\hat{S}_y,\hat{S}_z]$，其中

$$\hat{S}_x=\begin{pmatrix}0&0&0\\0&0&-\mathrm{i}\\0&\mathrm{i}&0\end{pmatrix},\hat{S}_y=\begin{pmatrix}0&0&\mathrm{i}\\0&0&0\\-\mathrm{i}&0&0\end{pmatrix},\hat{S}_z=\begin{pmatrix}0&-\mathrm{i}&0\\\mathrm{i}&0&0\\0&0&0\end{pmatrix}。\tag{1}$$

光的自旋角动量是$\hat{S}$作用于电磁场$\left|\psi\right\rangle=[\boldsymbol{E}(\boldsymbol{r}),\boldsymbol{H}(\boldsymbol{r})]$的期望值，

$$S=\left\langle\psi|\hat{S}|\psi\right\rangle。\tag{2}$$

如果只考虑电场的贡献，自旋可以写为$S\propto\mathrm{Im}\{\boldsymbol{E}^*\times\boldsymbol{E}\}$，其中Im表示取虚部，*表示复共轭。

收稿日期：2023-05-10；**修回日期**：2023-07-04；**录用日期**：2023-07-11；**网络首发日期**：2023-07-21

基金项目：国家重点研发计划（2022YFA1205100）、国家自然科学基金（12274296）、上海浦江人才计划、上海市科委国际合作项目（22520714300）、阳阳发展基金

通信作者：*wangbo89@sjtu.edu.cn

对于自由空间传播的平行光，有两种自旋本征态，即 $S=\sigma^{\pm}P/|P|$。这里，$P=\mathrm{Im}\{E^{*}\times H\}/2$ 是坡印廷矢量，$\sigma^{\pm}$ 分别表示右旋或左旋圆偏振态，等价于每个光子分别具有 $\pm\hbar$ 的自旋角动量。空间传播的平面光只有纵向自旋（$S/\!/P$），这是由光的横波性 $\nabla\cdot E=0$ 所保证。对于傍轴近似的光束，任意的偏振态都可以对应于Poincaré球面上的一个点。其中，圆偏振态处于Poincaré球面上的北极和南极，分别有斯托克斯参量 $S_3=\pm1$（图1）。非傍轴光束则具有更加广义的三维偏振态，其描述可以采用Majorana球，有兴趣的读者可以参看文献[2]。自旋本征态构成基矢空间，因此可以用自旋作为自由度进行光场调控和光与物质相互作用研究，并由此衍生出自旋光学领域。

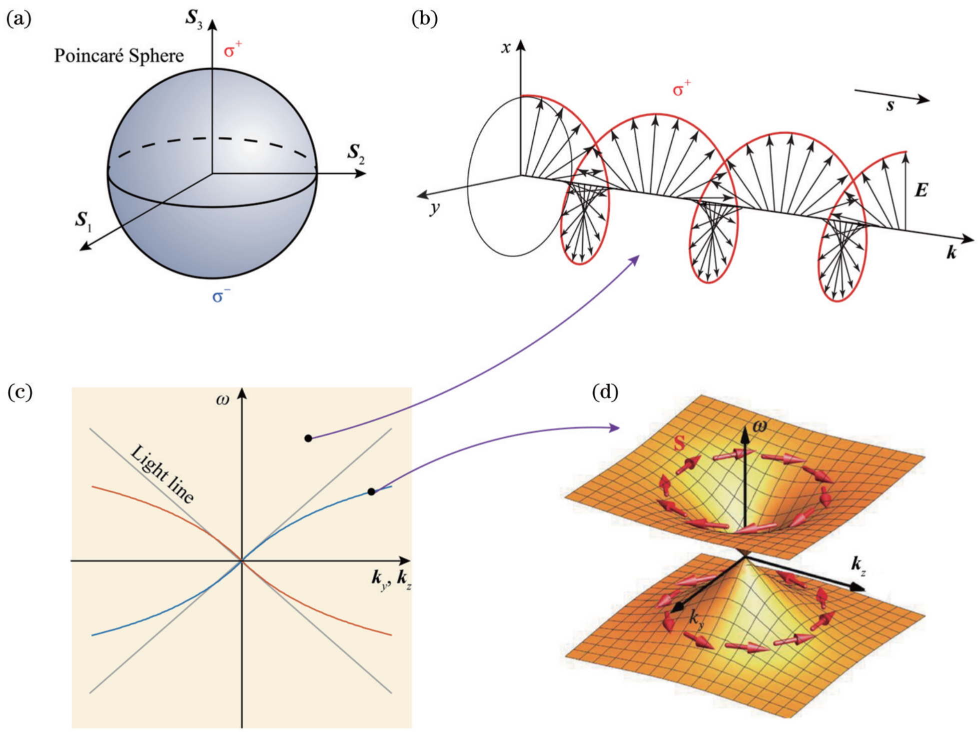

图1 光场自旋的表示。(a)Poincaré球，圆偏振态处于Poincaré球面上的北极和南极；(b)圆偏振光的电场分量在传播过程中绕波矢 $\boldsymbol{k}$ 旋转；(c)(d)自由传输光与倏逝波的自旋区分(自由空间传输光只具有纵向自旋，倏逝波的自旋是横向自旋)[13]

Fig. 1 Photonic spin and its presentation. (a) Poincaré sphere, left-handed and right-handed circular polarization are located at the south and north poles of the Poincaré sphere, respectively; (b) electric field of the circularly polarized light rotates around the wave vector $\boldsymbol{k}$; (c)(d) difference of spin between free-space propagated light and evanescent waves (light possesses longitudinal spin in free-space propagation, while it exhibits transverse spin in evanescent waves)[13]

当光与物质相互作用时，往往会产生结构光场，例如非傍轴光[3]、倏逝波[4]、布洛赫波、表面等离激元[5-7]、波导[8]或驻波共振模式等。它们的动量描述需要根据矢量场的特点进行修正[9-10]。具体地，坡印廷矢量将由两项组成：轨道动量 P_o 和自旋动量 P_s。其中，轨道动量 $P_o=\mathrm{Im}\{E^{*}(\cdot\nabla)E\}$，它代表光场的局部动量或者正则动量，这一项在傍轴光的情况下等于坡印廷矢量。自旋动量的形式是 $P_s=\nabla\times S/2$。自旋动量的概念早先由Belinfante[11]在描述量子粒子的自旋时提出，随后被引入电磁波。自旋动量的形式表明，自旋的旋度对电磁波有额外动量贡献。比如，Albaladejo等[12]通过麦克斯韦压力张量计算且发现光散射力除了包含坡印廷矢量导致的辐射压力以外，还有一个额外的非保守力的贡献。该力与光场的自旋角动量旋度成正比，也就是来源于 P_s。对于任意矢量光场，均有 $P=P_o+P_s$。此外，光还具有轨道角动量 $L=r\times P_o$[13]，轨道角动量在光具有横向结构分布或者波前相位涡旋时出现，并可能与自旋角动量发生耦合，产生自旋分离效应。

光在传播方向上具有动量和自旋角动量的特点早已为人们所熟知。然而，直到最近人们才意识到光能携带横向于光运动方向的自旋角动量[3]。光的横向自旋产生于倏逝波中，如表面等离激元[14]、波导模式[15]等。对于具有单一波矢量的倏逝波，自旋的方向始终垂直于传播方向($\boldsymbol{k}$)和光场指数衰减方向(z)，并符合右手定则 $S/\!/k\times z$，这一效应被称为横向自旋的锁定效应[14,16][图1(d)]。Shi等[17]近期的研究则表明，横向自旋与动量在一般的倏逝场中具有普遍意义的关系：

$$S=\frac{1}{2\omega^2}\nabla\times P。\qquad(3)$$

这一结果揭示了光场横向自旋与动量之间深刻内在关联，并导致了光自旋斯格明子(skyrmion)或者半子(meron)等新奇光场自旋模式的发现[18-19]。横向自

旋的研究使自旋在纳米光学、生物传感和近场显微镜等众多应用成为可能，也可以借助其实现对原子、分子和纳米结构的三维控制，获得手性纳米光子和等离激元光学器件。

2 光自旋现象机理与应用

2.1 光的自旋轨道耦合

尽管自旋是光的内禀性质，它不依赖于空间坐标，但是在光的传播、散射、干涉等过程中，自旋与动量或者轨道角动量之间会发生耦合。结果就是光场的自旋在空间重新分配，可以由几何相位[20-21]、角动量转换、空间反演对称破缺等一系列机理予以解释。特别地，波长尺度的空间结构变换往往对应显著的自旋轨道耦合效应。因此在微纳光学范畴，自旋轨道耦合十分普遍，对基本的光学测量、光场调控以及光和物质相互作用带来了不可忽略的影响。

光的自旋霍尔效应（PSHE）是典型的光学自旋轨道耦合的结果[22-23]。它指的是光束在传播过程中左、右旋的重心发生分离的现象，类似于电子在自旋轨道耦合过程中发生的劈裂。例如，当偏振的高斯光束以非正入射角照射到均匀介质界面上发生反射或者折射时［图 2(b)］，就会产生 PSHE[24-29]。这里产生 PSHE 的原因可以简单解释如下：高斯波包由一系列平面波组成，每一个平面波以微小不同的入射角达到界面。根据折射定律，界面对高斯波包中不同平面波成分重新进行了偏振选择，最终导致左、右旋发生分离。这种偏振选择原理也可以解释为光束发生方向突变产生的几何相位。均匀界面产生的 PSHE 一般很弱，左、右旋之间的分离量远远小于光斑半径。因此需要根据量子弱测量原理对偏移信号放大进而实现测量[27]。一个特殊的例子是当入射角位于布鲁斯特角附近时，光自旋霍尔分离可以获得放大。布鲁斯特角附近的 PSHE 对入射角度非常敏感，因此可以用于精密光学测量[30-33]。近些年来，均匀界面的 PSHE 已有大量的研究工作，有兴趣的读者可以通过相关综述进一步了解[34-35]。

当傍轴光的传播方向在空间缓慢变化时，其偏振也会进行相应的旋转［图 2(a)］。这种偏振旋转效应可以用动量空间中的几何相位解释，表示为光在布洛赫球面的绝热演化过程[4,21]。具体地，线偏振光在随体坐标下发生旋转，其效果类似于受到了自旋依赖的磁场作用。因此，左、右旋分量分别获得相反的几何相位。这种几何相位效应（偏振旋转效应）早期在弯曲的光纤中就已经被发现[36]。但是由于光被束缚在光纤里，左、右旋不会发生相对的重心移动。2009 年，Bliokh 等[4]将空间光耦合到圆柱形玻璃里，通过光在玻璃内表面持续全内反射而实现光束螺旋运动。由于不受波导对光的空间模式限制，左、右旋的分离通过几何相位的累积而逐渐放大，并最终观察到 PSHE。

文献［16］证明了倏逝波模式的自旋动量锁定能够表现出固有的量子自旋霍尔效应，即光沿界面表面的单向自旋传输现象［图 1(d)和图 2(c)］。自旋动量锁定源于麦克斯韦方程中倏逝波的基本性质，并且可以在支持表面倏逝波或波导模式的任何真空-介质界面上观察到。特别地，金属真空界面处的表面等离激元表现出了类似于拓扑绝缘体表面态的特征，在锥形色散面上具有自旋涡旋分布特点［图 1(d)］。但是需要指出的是，表面等离激元的色散并没有打开的拓扑能带结构。因此这种光的量子自旋霍尔效应并不受拓扑保护。比如，在表面放置纳米颗粒或者光栅结构会使光散射或者耦合到自由空间。另外，横向自旋也是不同表面矢量波的普遍特征，它不仅出现在光波中，还可能出现在弹性介质波和表面水波之中。

利用人工设计的亚波长结构可以实现显著、高效率的光子自旋霍尔效应：左、右旋在动量空间完全分离[37-40]。2001 年左右，Hasman 课题组[39,41-42]利用亚波长尺度光栅结构还了一套平面几何相位光学元件，称为 Pancharatnam-Berry Phase Optical Element，简称 PBOE［图 2(e)］。对于一个各向异性纳米结构，若其主轴方向在 xy 平面内与 x 方向呈夹角 θ，那么当一束圆偏振光正入射打到该结构上时，结构单元将会使得透射光产生相反的圆偏振光，并且获得相位突变，即 $\left|\sigma^{\pm}\right\rangle \rightarrow \exp\left(-2\mathrm{i}\sigma^{\pm}\theta\right)\left|\sigma^{\mp}\right\rangle$。这里产生的相位 $-2\sigma^{\pm}\theta$ 被称为 Pancharatnam-Berry 相位，是偏振状态在庞加莱球面演化的结果。相位的命名缘由是印度科学家 Pancharatnam 早期在研究矢量光干涉的时候发现了这一效应[20]，后来 Berry[21]研究二能级量子系统在布洛赫球面绝热演化过程中也导出了类似效应，因此被称为几何相位或者 Pancharatnam-Berry 相位[43]。PBOE 是大家目前所熟知的几何相位超构表面的早期构型[44-45]。这里，亚波长光栅结构是为了实现半波片功能，从而使入射光几乎全部转换到相反圆偏振态，实现高效率的利用。当平面光入射到 PBOE，并且光栅角度的面内分布满足简单的线性关系时，出射光与入射光的动量符合，

$$\boldsymbol{K}=\boldsymbol{k}-\sigma\boldsymbol{\Omega}, \tag{4}$$

式中：$\boldsymbol{K}$ 被称为广义动量，它是原入射光平行于面内的动量 $\boldsymbol{k}$ 受到自旋依赖的几何相位调制结果[6]；$\boldsymbol{\Omega}=2\nabla\theta$ 是各向异性结构的主轴在空间旋转率，等效为一种赝磁矢势。式(4)中的广义动量描述了几何相位超构表面的自旋轨道耦合，它使得入射光的左、右旋分量在动量空间中劈裂，产生光的自旋霍尔效应。此外，不依赖于自旋的广义动量也可以用于解释超构表面中提出的广义折射定律[44]。

光子晶体（平板）是与超构表面非常类似的一类人工结构，由亚波长量级的周期性高折射率和低折射率材料在平面内重复排列组成。在光子晶体中引入结构的反向对称破缺会产生自旋分离的能带结构。例如，

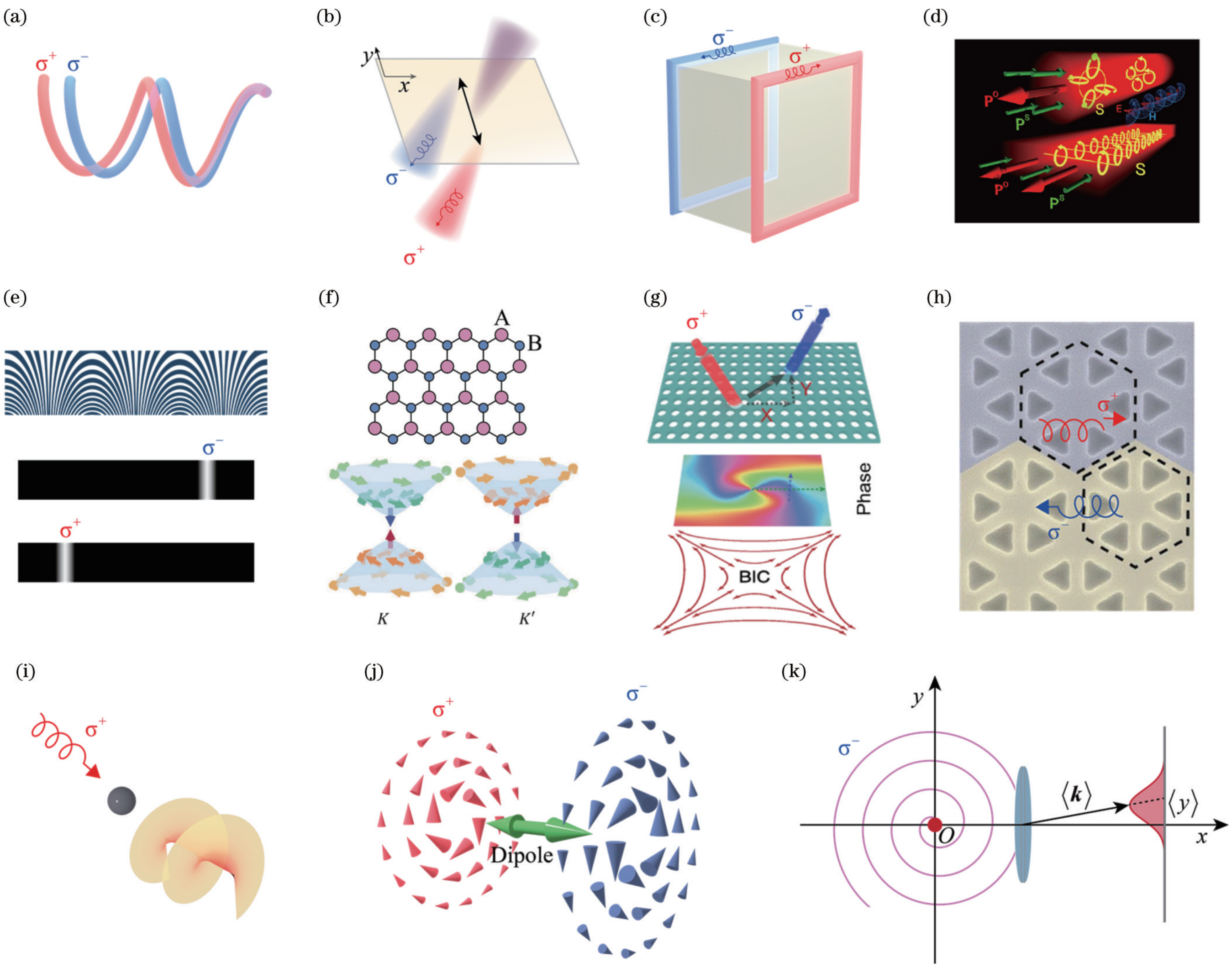

图 2 微纳光学中无处不在的自旋轨道耦合现象。(a)光在圆柱玻璃内表面持续全内反射实现左、右旋的分离[4];(b)偏振的高斯光束以非正入射角打到均匀介质界面上反射或者折射时产生光子自旋霍尔效应[24];(c)倏逝波模式的自旋动量锁定表现出固有的量子自旋霍尔效应[16];(d)波导中的光自旋分布[15];(e)亚波长尺度的光栅结构实现的光子自旋霍尔效应[41];(f)具有两个不等价的格点 A、B 的蜂窝状构型的二维光子晶体导致光子晶体能带结构形成上、下一对自旋锁定的能谷[46-47];(g)BIC 周围拓扑涡旋的强自旋轨道耦合实现光子自旋霍尔效应[52];(h)两种不同的光子拓扑绝缘体边界实现单向自旋光量子传输[54];(i)亚波长尺度的球形纳米颗粒被平行光照射后发生散射会产生涡旋光束[58];(j)线偏振偶极辐射近场具有自旋态[60];(k)圆偏振偶极辐射在远场会发生波长量级的重心偏移[56]

Fig. 2 Ubiquitous spin-orbit coupling phenomena in micro- and nano-optics. (a) Separation of left-handed and right-handed circularly polarized light is induced by continuous total internal reflections of light on the inner surface of a cylindrical glass[4]; (b) when a polarized Gauss beam illuminates a homogeneous air-dielectric interface, the reflected or refracted light exhibits a PSHE[24]; (c) spin momentum locking of evanescent waves exhibits an intrinsic quantum spin hall effect of light[16]; (d) spin distribution of light in the waveguide[15]; (e) PSHE is realized by spatial-varying sub-wavelength grating structures[41]; (f) spin locking at the energy-momentum bandstructure valley from a photonic crystal slab in a honeycomb configuration[46-47]; (g) strong spin orbit coupling implementation of topological vortices around BIC[52]; (h) boundary of two different photonic topological insulator performs light quantum transmission with unidirectional spin[54]; (i) a vortex is generated when a circularly polarized plane wave illuminates a sub-wavelength spherical nanoparticle[58]; (j) near field of linear polarized dipole possesses spin angular momentum[60]; (k) radiation of a circularly polarized dipole induces wavelength scale centroid deviation in the far field[56]

蜂窝状构型的二维光子晶体具有两个不等价的格点 A、B,这会导致在光子晶体能带结构的第一布里渊区高对称点(K, K')形成狄拉克点[图 2(f)]。当通过尺寸或者形状的调制 A、B 格点的结构不一样时,狄拉克点就可能被打开,形成上、下一对自旋锁定的能谷[46]。对于能谷的导带(或者价带),K、K' 分别对应于自旋朝上(下)、下(上)。能谷周围的偏振状态(斯托克斯参量 S_1、S_2、S_3)可以用类似于磁性半子的拓扑结构描述[47]。具有二重旋转对称(C_2)的光子晶体,其能带中心对称点 Γ 点存在高品质因子、矢量拓扑所保护的连续域中

束缚态模式(BIC)[48-49]。完美BIC是动量空间的矢量光模式，可以表示为

$$|M_{\mathrm{BIC}}\rangle_k=\frac{1}{\sqrt{2}}\left(|l\rangle_k|\sigma^+\rangle+|-l\rangle_k|\sigma^-\rangle\right)。\quad(5)$$

式(5)可以将BIC模式当作动量空间具有相反轨道角动量$l(-l)$的自旋轨道纠缠模式。当正入射的圆偏振光照射到该结构，并且用相反的圆偏振检测时，将会获得涡旋光束[50]。进一步，C_2对称性破缺导致在BIC附近的能带产生成对且相反的圆偏振态[51]。近期，Wang等[52]通过BIC周围拓扑涡旋的强自旋轨道耦合实现光子自旋霍尔效应[图2(g)]。此外，光子晶体还可以构造光子拓扑绝缘体[53]。在两种不同的光子拓扑绝缘体边界，能够产生单向自旋传输的边界态[图2(h)]。将量子辐射源放置于这样的边界附近，辐射模式的传播方向与偶极辐射的自旋态锁定，可实现高鲁棒性的单向自旋光量子传输[54]。需要注意的是，这里的效应[图2(h)]与表面等离激元的量子光子自旋霍尔效应不同[图2(c)]。首先，拓扑光子晶体情形下的自旋是一种赝矢量，表示拓扑边界态的一对正交模式，与$\boldsymbol{S}$并不完全等价；其次，模式的单向传输可以受拓扑保护，因此能够越过障碍物、扰动或者缺陷。虽然偶极子辐射代表了最基本的光子源，但最近的一些研究仍然揭示了偶极辐射的一些奇特性质。比如，电偶极矩或磁偶极矩的组合(米氏散射)会导致定向的远场发射模式[55]、自旋劈裂、螺旋远场[56]、近场的定向耦合[57]等。这些研究结果可以产生纳米光学的各种应用，如光隔离器、波导耦合、位置传感、偏振开关等。在偶极子辐射这种非傍轴光场中，自旋轨道耦合不需要任何具有空间各向异性的结构，由非傍轴光场在传播过程中自然发生。这是因为，对于一个偶极矩$\boldsymbol{p}$，它在空间不同位置$\boldsymbol{r}$处辐射的电场$\boldsymbol{E}$[58]可以简单表示为

$$\boldsymbol{E}(\boldsymbol{r})\propto\frac{\hat{\boldsymbol{r}}\times(\hat{\boldsymbol{r}}\times\boldsymbol{p})}{r}。\quad(6)$$

由于$\hat{\boldsymbol{r}}\times(\hat{\boldsymbol{r}}\times\boldsymbol{p})=-\boldsymbol{p}+\boldsymbol{r}(\hat{\boldsymbol{r}}\cdot\boldsymbol{p})$，表明$\boldsymbol{p}$会在球面$\hat{\boldsymbol{r}}$方向上进行投影操作，也就是源的偏振$\boldsymbol{p}$会在空间中不同方向发生偏振变换。这一过程会产生几何相位，实现自旋轨道耦合。例如，平行光照射到一个亚波长尺度的球形纳米颗粒上发生散射会产生涡旋光束[图2(i)]。由于类似原因，光在聚焦、成像的过程中，自旋到轨道的转换也会发生[13]。近期，Liu等[59]发现偶极子辐射中交叉偏振分量可以写成平行分量的二阶空间微分形式。他们通过将这种偶极子辐射内在的空间偏导引入单光子显微成像技术，在低光子水平下清晰观测到了纯相位的透明物体，避免了对活细胞的生物物理损伤。一直以来，大家认为线偏振的偶极辐射不携带角动量，也不会出现自旋。但是近期的一些理论和实验都表明，线偏振偶极辐射近场可以具有很强的自旋态[60][图2(j)]，这些自旋信息可以通过近场波导耦合[60]或者各向同性纳米颗粒的再散射过程[61]传播到远场而被观测。与倏逝波的横向自旋不同，线偏振偶极子的自旋与辐射源的距离呈$1/r^3$衰减，因此在精密偏振光学相关应用中可能有不可忽略的影响。圆偏振的自旋轨道耦合研究得更早，其辐射会在垂直于自旋的平面内产生螺旋线型的能流。因此，远场测量圆偏振辐射重心会获得不能避免的波长量级位置错误[56][图2(k)]。此外，圆偏振偶极辐射的螺旋形能流具有方向选择性耦合特点，可以实现与波导模式的定向耦合。更一般地，电偶极子和磁偶极子的不同相位组合，可以形成Janus或者惠更斯极子。圆偏振电偶极子、惠更斯和Janus极子构成了所有可能的定向偶极子源的完整集合，它们能够实现定向发射、散射和波导耦合，为量子光学技术、集成纳米光子学和新超构表面的设计提供重要依据[62]。

2.2 PSHE与对称破缺

光与物质相互作用包含两个部分：光场$\boldsymbol{E}(\boldsymbol{r})$和物质$\epsilon(\boldsymbol{r})$。当光或者物质在二维平面内具有沿某一个方向的反演对称破缺时，例如$\epsilon(\boldsymbol{r})\neq\epsilon(-\boldsymbol{r})$，则自旋分裂发生在垂直于$z$和$\boldsymbol{r}$的方向，由角动量守恒保证。典型的现象有：光斜入射到均匀界面的光子自旋霍尔效应[26]、对称破缺的准BIC体系自旋能带[51]、以非对称中心打到颗粒散射出现的自旋现象[63]、几何相位超构表面[39]、谷光子晶体等[46]。这些效应都满足时间反演对称，即$I_{\sigma^+}(\boldsymbol{k})=I_{\sigma^-}(-\boldsymbol{k})$。左、右旋沿着某中心连线的重心劈裂形式类似偶极极化(图3)。当光场和物质在二维面内均保持了空间反演对称时，光子自旋霍尔效应不会发生，但是自旋分离现象以更高阶的自旋-轨道转换的形式存在，并且具有类似高阶极子的极化模式(图3)。例如：线偏振偶极子辐射的自旋模式(线偏振光颗粒散射、紧聚焦等)[60]、完美BIC模式的矢量光场[50]、偏振高斯光束正入射到均匀介质界面所观察到的轨道角动量现象等[64]。

2.3 自旋光学相关应用简述

伴随着PSHE概念的提出，自旋自由度在纳米光学领域获得了快速的发展和广泛的应用(图4)。其中，以几何相位为代表的纳米光学结构主要以光的自旋为基础实现光场控制，目前已经发展了多种超薄光学器件，实现了包括自旋光操控[65]、手性成像[66-67]、光学全息[68]、偏振光谱探测等系列应用[69-70]。光的自旋分离也被作为精密测量[71-72]，或者光学差分手段，用于产生图像的边缘成像[59,73-74]。几何相位结构对光产生的动量$\sigma\boldsymbol{\Omega}$可以被反向利用，使宏观物体获得自旋选择横向光力[75]。自旋-轨道转换原理还能被用于非线性转换过程[76]，产生量子纠缠态[77-78]、级联二次谐波等现象[79]。

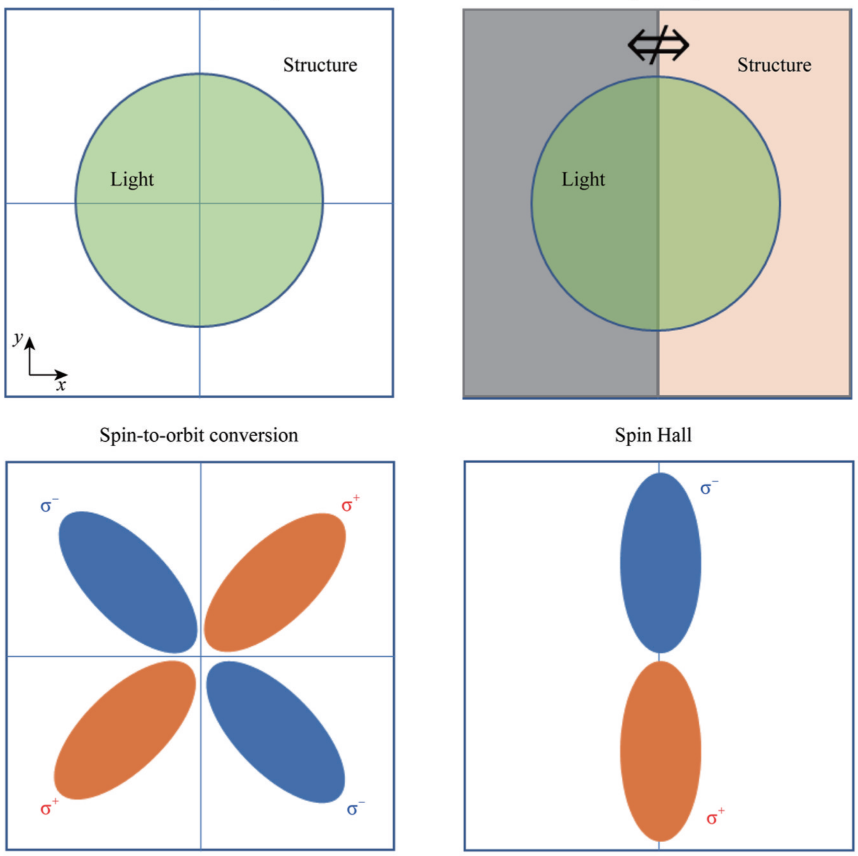

图 3　自旋分离现象和反演对称性破缺

Fig. 3　Spin split effects and inversion symmetry breaking

3　无序超构表面中的PSHE

3.1　各向异性无序的PSHE

光和无序结构的相互作用可以产生非常新奇的现象甚至难以预测的效应[80-82]。比如：将多层高、低折射率纳米薄膜交错堆叠在一起，这些薄膜约2 nm厚度的微弱无序可以产生安德森局域效应[83]；横向的无序结构能导致光场的异常传输和聚焦[84]。这些实验研究表明，即便在深亚波长的尺度下，基于有效介电常数的平均理论也有可能会因为空间无序而失效。

基于无序设计的超构表面还有一些潜在的应用：它可以消灭激光散射光斑、获得更好的波前整形；无序可以作为一种信息隐藏的手段；通过无序噪声的设计可以突破传统超构表面的信息容量极限，获得更多自由度的偏振波前控制等[85]。

本文根据文献[86]介绍无序几何相位超构表面中发生的光自旋传输效应、演化规律。类似地，在无序介质中连续传播所产生的PSHE可以参考另外两篇文献[87-88]。如图5(a)所示，普通超构表面所引发的局部动量 $\boldsymbol{K}^{\pm}=\sigma^{\pm}\boldsymbol{\Omega}$ 与光束整体的坡印廷矢量一致。因此，在空间中看到的光自旋位置即为 $\boldsymbol{K}^{\pm}$。当超构表面中纳米天线转角产生随机变化时，整体的动量效应 $\sum \boldsymbol{K}^{\pm}\approx 0$，直观上预测光束重心不会发生偏移。然而，实验上仍然可以观察到左、右旋劈开的现象，如图5(b)所示。

无序几何相位是由无序参数 $\varepsilon(0<\varepsilon\leqslant 1)$ 表征的，它表示了纳米天线旋转的角度范围 $\theta_{\varepsilon}(x,\ y)$。在这个角度范围内，天线的转角满足均匀的概率函数分布 $f_{\varepsilon}(\theta)=\{1/\varepsilon\pi,\ -\varepsilon\pi/2<\theta\leqslant\varepsilon\pi/2, 0\}$。因此，当 $\varepsilon=1$ 时，超构表面的无序程度最强，结构不存在一个各向异性的主轴，并且几何相位覆盖整个 2π 区域，这可以通过图6(b)的庞加莱球看到。相反，当 $\varepsilon=0$ 时，所有的纳米天线朝一个方向排列，不会实现任何空间相位梯度调制的作用。可以看到，如果用圆偏振光入射到不同的 ε 从0逐渐改变到1的无序超构表面，则相反圆偏振光的远场辐射将会发生一些变化。绝大多数情况下，远场模式是一个符合衍射极限的光斑，位于动量空间的中心。直到 $\varepsilon=0.95$ 左右，中心亮斑突然消失，取而代之的是铺满整个动量空间的散射光斑。

这个过程可以采用动量空间的信息熵来量化。动量空间的Shannon熵定义为 $H_{\mathrm{S}}=-\sum_{i} p_i\,\mathrm{lb}(p_i)$，其中 p_i 是动量空间的概率密度函数，可以由CCD相机捕获的动量空间强度分布得到。具体地，可以将动量空间的光强归一化，并且分为一系列离散值，p_i 则是不同强度在整个动量空间所占的比重，可以用统计直方图描

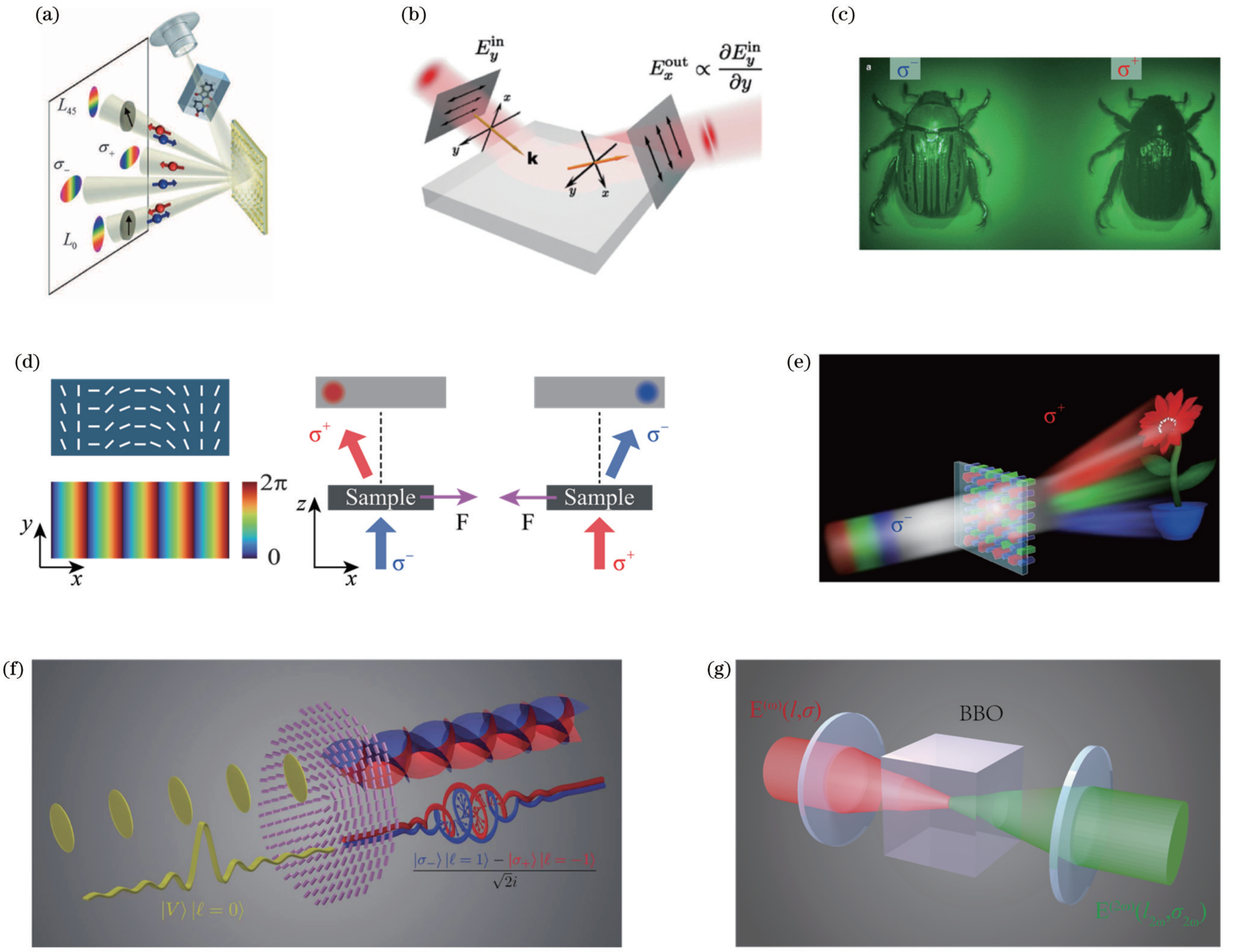

图 4 自旋光子学的广泛应用。(a)多功能几何相位超表面实现对手性分子的全斯托克斯参量测量[70];(b)自旋分离的光在各向同性的光学平面界面发生空间微分[73];(c)超透镜多光谱手性成像[66];(d)光对几何相位结构的宏观自旋光力[75];(e)介质超表面实现多波长可见光全息图[68];(f)超材料产生自旋-轨道角动量量子纠缠光子对[77];(g)携带角动量的基频光产生一系列携带不同角动量的二次谐波[79]

Fig. 4 Applications of spin photonics. (a) Full stokes parameter measurement of chiral molecules is realized by a multifunctional geometry phase metasurface[70]; (b) spatial differentiation of spin-separated light in an isotropic optical plan interface[73]; (c) multispectral chiral imaging by metalens[66]; (d) macroscopic spin optical force of light on the geometry phase structure[75]; (e) multi-wavelength visible holograms is realized by dielectric metasurface[68]; (f) quantum entangled photon pairs generated by metamaterials[77]; (g) second harmonic wave carrying a series of different orbiital angular momentum is generated by the fundamental spin polarized light[79]

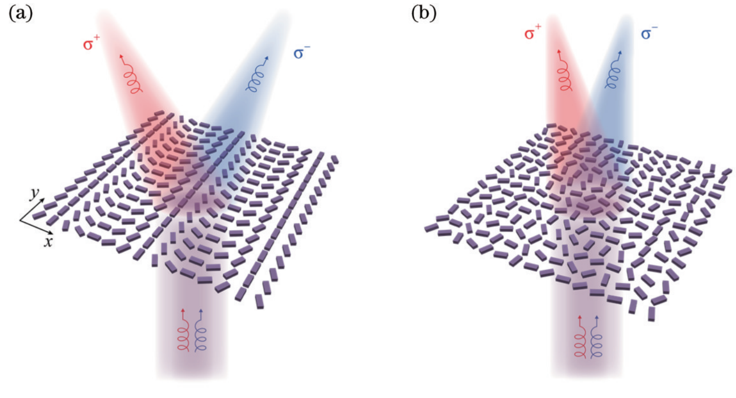

图 5 超构表面导致自旋霍尔效应示意图。(a)典型闪耀光栅几何相位分布导致的光自旋分离;(b)无序超表面引起的自旋分离现象

Fig. 5 PSHE from order or disordered geometric phases. (a) PSHE induced by a conventional blazed grating geometric phase distribution; (b) PSHE induced by a disordered geometric phase metasurfce

述。实验中，Shannon熵在无序参数接近1的时候实现了一个很陡直的上升过程，类似于一种相变现象。不过相变的理解仍然存在争议，因为临界点位于参数范围的最大值（$\varepsilon=1$，对应于温度为无穷大）。尽管如此，这一演化过程依然十分有趣，它量化了光学散射在亚波长无序度逐渐增大过程中的统计分布。

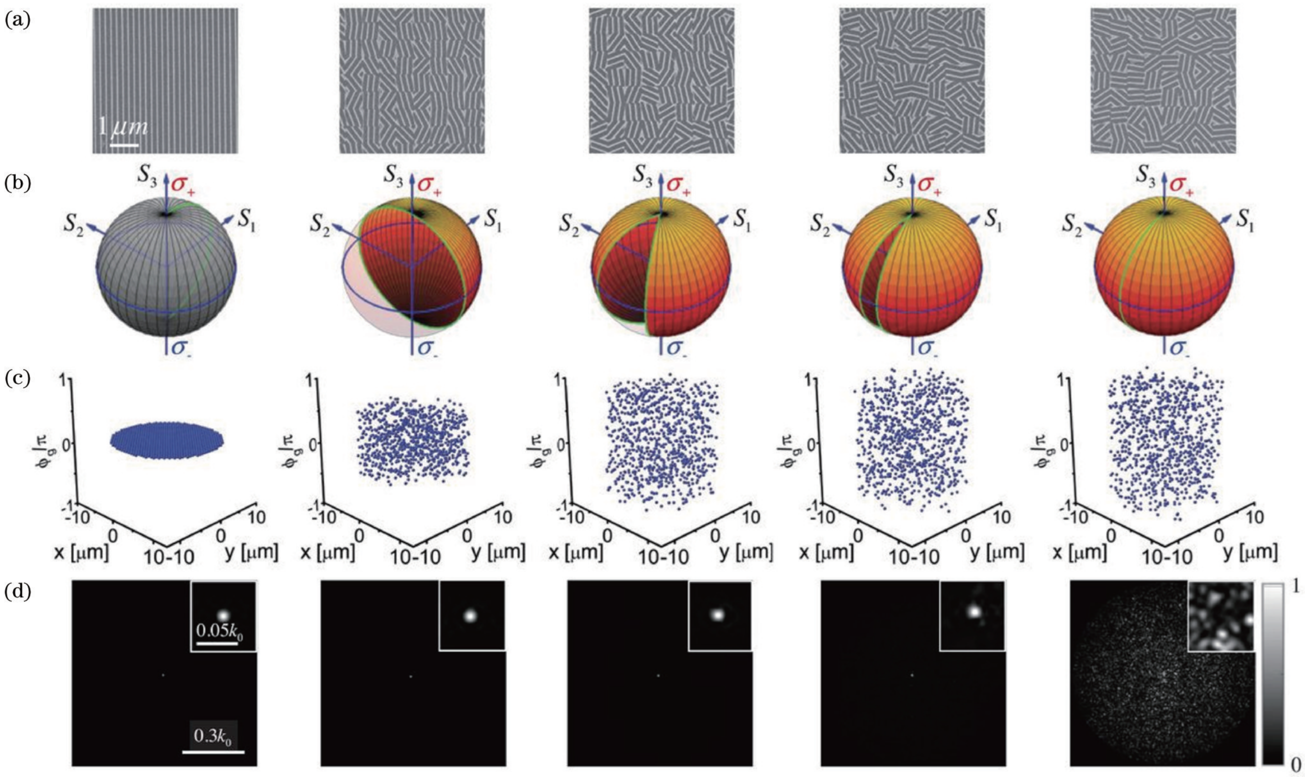

图6 动量空间中的自旋分裂模式[86]。(a)不同无序参数（ε=0、0.5、0.85、0.95和1，从左到右）的无序超构表面扫描电子显微镜图；(b)通过庞加莱球面获得几何相位的示意图；(c)不同ε值的无序几何相位的分布；(d)无序几何相位导致的动量空间强度分布

Fig. 6 Spin splitting patterns in momentum space[86]. (a) Scanning electron microscopic images of metasurfaces with different disorder parameter (ε) values (0, 0.5, 0.85, 0.95, and 1, from left to right); (b) different geometric phase pick-ups represented on the Poincaré sphere; (c) spatial phase distributions of the disordered geometric phase for different ε values; (d) measured momentum space intensity distributions of light from disordered geometric phases

在$\varepsilon<0.95$的范围内，左、右旋光的重心向相反的方向偏移，产生了光子自旋霍尔效应。但这个偏移量远小于光斑尺度，因此需要借助量子弱测量技术。当$\varepsilon>0.95$时，左、右旋无序分散到整个动量空间。但是通过求关联函数可以发现，所有无序结构的散射都能满足$I_{\sigma^+}(\boldsymbol{k})=I_{\sigma^-}(-\boldsymbol{k})$（图7），由时间反演对称保证。无序的研究激发了人们对此现象的兴趣，但是并没有从物理上解释无序体系中光子自旋霍尔效应的起源。

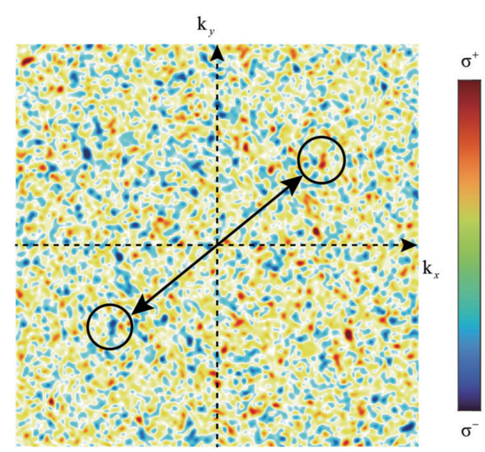

图7 随机几何相位结构中自旋分离效应的时间反演对称性

Fig. 7 Time-reversal symmetry of spin split effects in random geometric phase structures

3.2 拓扑PSHE

拓扑霍尔效应也许是大家比较陌生的一种效应[89]。电子在材料中的自旋输运起源可以被划分为三类：由外磁场导致的正常霍尔效应（1897，Hall）、磁化导致的反常霍尔效应（1881，Hall），以及后来发现的由于存在磁性拓扑缺陷斯格明子而导致的拓扑霍尔效应[89-90]。与铁磁或反铁磁相互作用形成的平面涡旋结构不同，斯格明子是由于磁矩之间的Dzyaloshinskii-Moriya相互作用形成的具有三维矢量分布拓扑缺陷，其拓扑核需要以$N_{sk}=(1/4\pi)\iint m\cdot\left[(\partial m/\partial x)\times(\partial m/\partial y)\right]\mathrm{d}x\mathrm{d}y$的积分形式描述。$N_{sk}=\pm1$时，缺陷结构为斯格明子，$N_{sk}=\pm1/2$为半子。电

子经过斯格明子的时候会产生自旋轨道耦合，获得实空间Berry相位。斯格明子等效于一个磁场奇点，使电子受洛伦兹力的影响而发生偏折[91]。理论上，自旋相反的电子受到的等效磁场是反向的，因此会有自旋霍尔效应的产生(图8)。

在光学领域，Tsesses等[92]计算了表面等离激元干涉所产生光学斯格明子的光力效果，这种力可能会使微粒受到类拓扑霍尔效应的输运作用。Karnieli等[93]则在非线性光学系统中实现了类似拓扑霍尔效应的光输运特点。

超构表面对光自旋的几何相位和Berry相位机理相同，因此原理上也能产生类似的自旋霍尔效应。图9展示了两种平面相位分布及其可以等效为磁场与磁矢势的形式。对于一个任意的二维相位分布$\phi(\boldsymbol{r})$，空间梯度表示局部动量$\boldsymbol{K}=\nabla\phi(\boldsymbol{r})$。一般情况下有$\nabla\times\boldsymbol{K}=0$成立，即相位梯度的分布无旋。但是在无序相位体系里，有一定的概率使得$\nabla\times\boldsymbol{K}\neq 0$，这些点就是相位奇点，或者相位涡旋的中心。作为与电子获得动量的过程类比，可以将上述符号改写。局部动量改写为等效磁矢势$\boldsymbol{K}=\boldsymbol{A}_{\mathrm{eff}}=\nabla\phi(\boldsymbol{r})$，那么等效磁场为

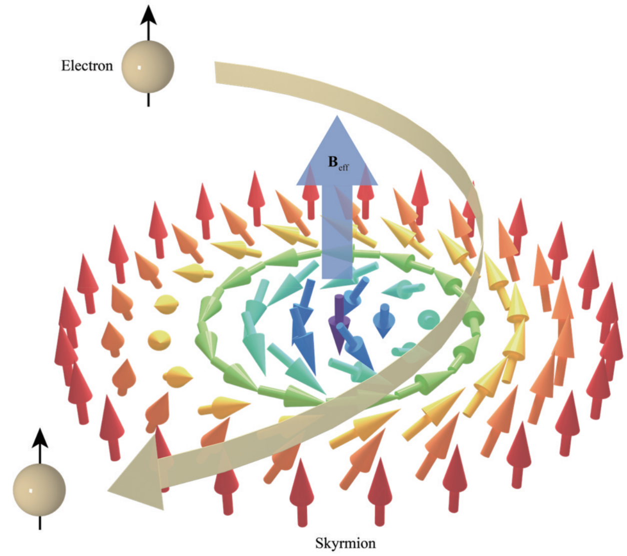

图8　电子的拓扑自旋霍尔效应示意图

Fig. 8　Topological Hall effect of electron

$\boldsymbol{B}_{\mathrm{eff}}=\nabla\times\boldsymbol{A}_{\mathrm{eff}}=\nabla\times\nabla\phi(\boldsymbol{r})$，等价为涡旋的拓扑荷$l=(1/2\pi)\oint\boldsymbol{A}_{\mathrm{eff}}\cdot\mathrm{d}\boldsymbol{r}=(1/2\pi)\oiint B_{\mathrm{eff}}\mathrm{d}S$。因此，相位涡

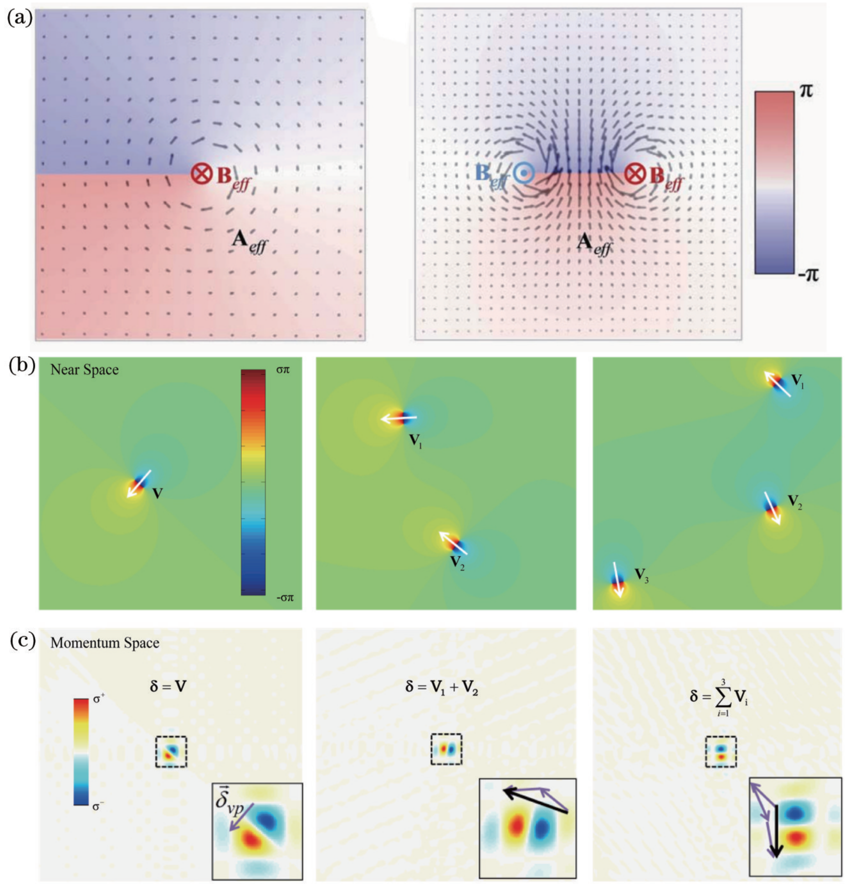

图9　涡旋引发的光子拓扑自旋霍尔效应[94]。(a)拓扑核和等效磁场示意图；(b)近场相位涡旋对示意图；(c)多个几何相位涡旋对产生的光子自旋霍尔效应符合矢量叠加原理

Fig. 9　Photonic topological spin Hall effect and vortex pairs[94]. (a) Schematic of topological defects and effective magnetic field; (b) schematic of vortex pairs in the near field; (c) PSHE generated by multiple geometry phase vortex pairs obeys the principle of vectoral superposition

旋等价于磁场奇点。当平面相位分布有两个拓扑荷相反的涡旋时，会形成涡旋对（vortex pair），面内具有非零磁矢势$\langle A_{\mathrm{eff}}\rangle$，导致光的偏折$K_{\mathrm{out}}=K_{\mathrm{in}}+\langle A_{\mathrm{eff}}\rangle$。这是由涡旋对相位这种离散拓扑结构形成的光霍尔效应现象。更进一步，$\phi(r)=\phi_0(r)+\phi_g(r)$，前者是偏振无关的相位（比如，动力学相位或共振延迟相位），后者是几何相位。几何相位将导致左、右旋之间的劈裂，产生光子自旋霍尔效应。这种由涡旋对相位导致的PSHE被称为拓扑光子自旋霍尔效应[94]。涡旋对相位可以由人为设计而产生，也可以是无序相位传播中产生。更重要的是，由涡旋对引起的光拓扑自旋霍尔效应可以映射为二维XY模型的哈密顿量，因此可能用于探测 Berezinskii-Kosterlitz-Thouless 拓扑相变[95]。

3.3 无序磁光导致的PSHE

光不携带电荷，因此不与磁场发生相互作用，但是磁化的介质却会影响光的传播。均匀磁化的介质会改变光的偏振状态，产生磁光法拉第效应或者磁光克尔效应。根据这个原理可以制作光隔离器。不均匀的磁化则可能导致光场的轨迹变化，产生类似于霍尔效应的光学对应体。这里的光霍尔效应由真实磁场导致，而非赝磁场或者几何相位。例如，Rikken 等[88,96]预言并且在实验中证明，光在加载了磁场的随机介质中传播会出现横向扩散。磁场的存在打破了时间反演对称性，干扰了光在随机介质中传播的背向散射。Karpai 和 Weitz[97]实验研究了电磁感应透明条件下，圆偏振光束在铷蒸气室中发生的光束偏转，实现了类似 Stern-Gerlach 磁场梯度中的银原子偏转现象。磁光克尔效应描述了从磁化材料反射的线性偏振光的偏振旋转。通常而言，由于光与物质相互作用的长度有限，铁磁金属薄膜的克尔效应非常弱。然而，金属纳米结构可以利用等离激元共振来显著增强效果。文献[98]通过无序的磁化产生随机几何相位可以获得PSHE（图10）。测量PSHE的概率分布可以检测超构原子的极弱半径

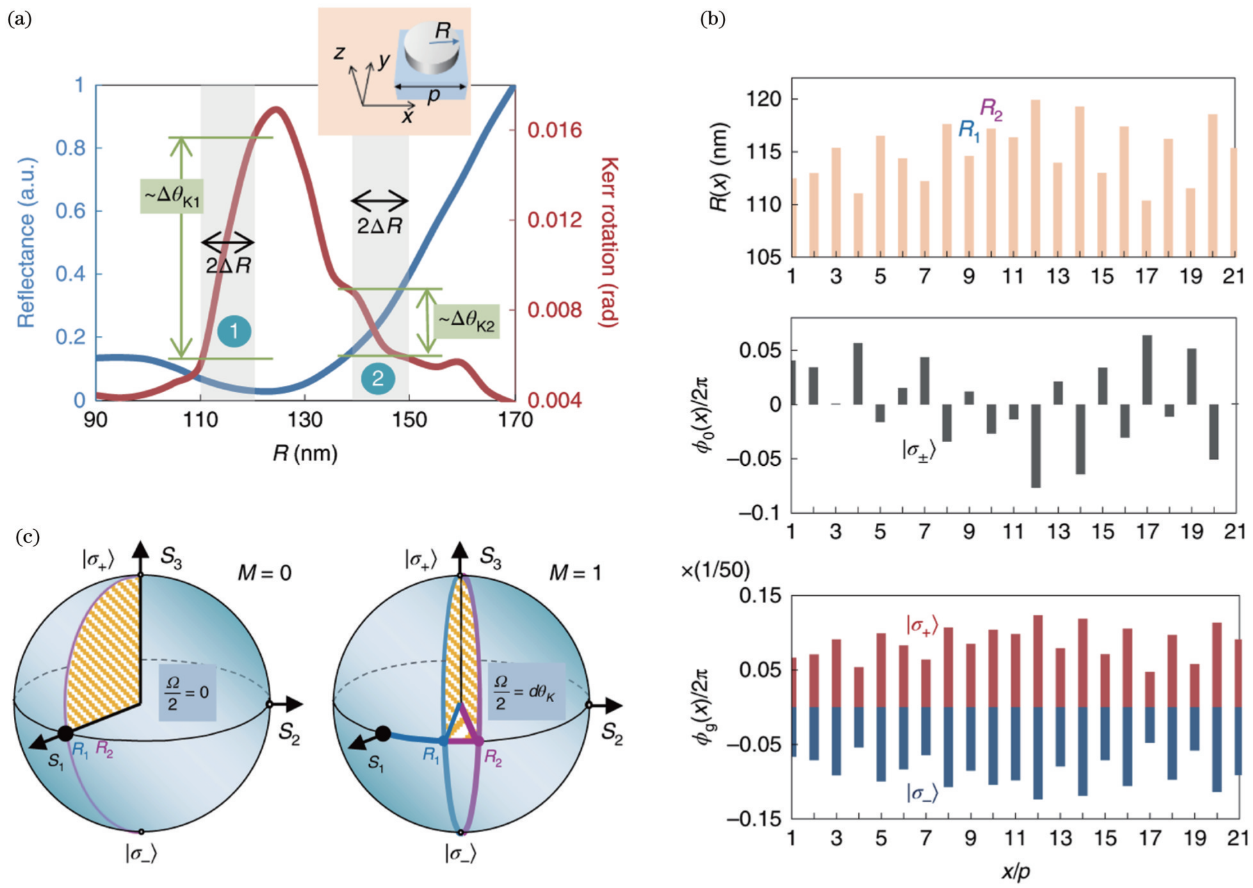

图10 磁光克尔效应、Pancharatnam-Berry 相位和无序铁磁超表面导致的PSHE[98]。(a)磁光克尔旋转θ_K和反射强度的计算值与圆形镍纳米天线半径R的函数关系；(b)计算出的超原子半径分布为$R(x)$的一维无序超表面的共振相位$\varphi_0(x)$和几何相位$\varphi_g(x)$；(c)使用半径为R_1和R_2的两个原子在庞加莱球上解释的磁化诱导几何相位（左图和右图分别显示了超表面磁化之前和之后的情况）

Fig. 10 Kerr rotation, geometric phase and PSHE from a disordered ferromagnetic metasurface[98]. (a) Calculated Kerr rotation θ_K and reflection as a function of the radius R of circular nickel nanoantennas in a periodic lattice; (b) calculated resonant phases $\varphi_0(x)$ and geometric phases $\varphi_g(x)$ of an example 1D disordered metasurface with a radius distribution $R(x)$ for the meta-atoms; (c) magnetization-induced geometric phase interpreted on the Poincaré spheres using two meta-atoms with radii R_1 and R_2 (left and right panels show the cases before and after the metasurface is magnetized, respectively)

波动。这种敏感效应可能适用于检测片上纳米器件的纳米级制造误差。本质上，光的自旋位移是由空间变化的几何相位相引起的，由有限空间无序系统中的磁光效应产生。除了共振结构的尺寸波动，磁光效应的涨落可以由磁化强度或磁场的空间涨落实现，可以通过PSHE对这些现象进一步探索。

3.4 随机偶极辐射的光自旋分离

量子点、半导体二维材料、钙钛矿颗粒，以及一些原子或分子的发光可以认为是时间上随机产生、空间上无序分布的偶极子辐射。对这种辐射实现高效的偏振、相位控制需要采用非一般超构表面的器件。从物理层面上讲，微纳结构需要满足两个功能：1)对光进行空间选模，获得良好的空间相干光；2)利用额外的结构或者几何变量对这种相干光实现相位控制而辐射。文献[61]利用几何相位光子晶体实现了对二维材料、量子点等自发辐射光的自旋调控[图11(a)]。在通常的光学超构表面器件中，每个纳米结构的功能都是对自己所在区域的入射光附加相位、调控振幅、改变偏振。这很难对随机辐射的偶极子实现有效控制[图11(d)]。为了解决这个问题，作者首先设计了具有禁带的光子晶体，然后嵌套加入几何相位超构表面结构，实现局部的缺陷态模式。这些缺陷态模式不仅实现了局部的Purcell效应，即光的定位辐射，还选择了辐射的偏振。通过紧束缚耦合，每个偶极辐射的光都可以传播到近邻纳米结构获得几何相位的积累，从而以设计好的动量辐射到空间[图11(c)]。这种方式成功实现了对随机量子点、二维材料的辐射方向和自旋控制，激发了对包含量子发射器和超表面的异质结构的进一步研究。相似地，利用准BIC构型、能带折叠等手段也能实现类似功能[99-101]。

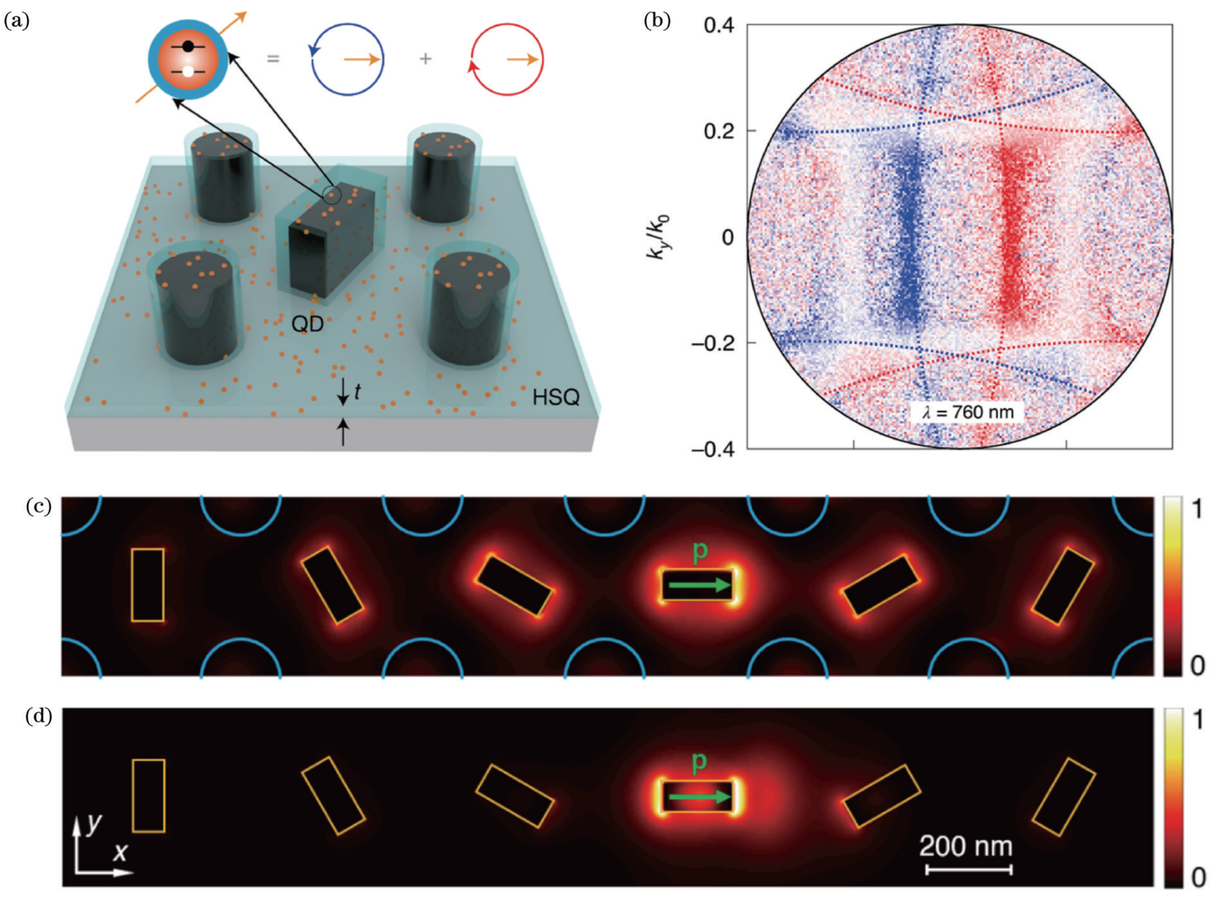

图11 几何相位光子晶体调控量子点辐射的自旋态[61]。(a)与量子点结合的Pancharatnam-Berry相位光子晶体示意图；(b)在动量空间中测量的自旋分裂模式[红色(σ^+)和蓝色(σ^-)曲线表示基于自旋-轨道动量匹配条件的计算值]；(c)几何相位光子晶体中，偶极辐射可以与近邻纳米天线耦合获得几何相位积累；(d)几何相位超表面中，偶极辐射难以到达近邻纳米天线获得几何相位

Fig. 11 Manipulate the spin of quantum dots emission by a geometric phase photonic crystal[61]. (a) Schematic of the Berry-phase defective photonic crystal incorporated with quantum dots; (b) measured spin-split modes in momentum space [dotted red (σ^+) and blue (σ^-) curves denote calculations based on the spin-orbit momentum-matching condition]; (c) dipole radiation can be coupled with adjacent nano antennas to obtain geometric phase accumulation in geometric phase photonic crystals; (d) dipole radiation is difficult to reach adjacent nano antennas to obtain geometric phase in geometric phase metasurfaces

4 结束语

如我们在过去二十年中所看到的那样，光学自旋轨道耦合现象在纳米级系统中几乎无处不在。对这些现象的深入理解不仅有助于基础物理研究，还扩展了众多的应用领域。如今，当纳米光子学发展面临更加极端条件的情况下，研究不同光子统计(荧光、激光和量子发射)的光自旋产生、操纵和检测是未来一个有希望的方向。从纳米光学结构出发，自旋会朝着更小的结构尺度[18]、更高的时空精度[102]、合成维度[103-105]、量子光学[78,106]、非线性等领域扩展。从光与物质相互作用来讲，自旋光学对磁性材料的磁序、相变、拓扑结构的泵浦和探测仍然具有重要的潜在价值。特别地，人工自旋冰领域的磁性现象与光子自旋霍尔效应具有深刻的内在联系，两者的结合可能具有新物理与技术的发现[107]。

参 考 文 献

[1] Castelvecchi D. The stern-gerlach experiment at 100[J]. Nature Reviews Physics, 2022, 4(3): 140-142.

[2] Bliokh K Y, Alonso M A, Dennis M R. Geometric phases in 2D and 3D polarized fields: geometrical, dynamical, and topological aspects[J]. Reports on Progress in Physics, 2019, 82(12): 122401.

[3] Aiello A, Banzer P, Neugebauer M, et al. From transverse angular momentum to photonic wheels[J]. Nature Photonics, 2015, 9(12): 789-795.

[4] Bliokh K Y, Niv A, Kleiner V, et al. Geometrodynamics of spinning light[J]. Nature Photonics, 2008, 2(12): 748-753.

[5] Luo X G, Pu M B, Li X, et al. Broadband spin Hall effect of light in single nanoapertures[J]. Light: Science & Applications, 2017, 6(6): e16276.

[6] Bliokh K Y, Gorodetski Y, Kleiner V, et al. Coriolis effect in optics: unified geometric phase and spin-Hall effect[J]. Physical Review Letters, 2008, 101(3): 030404.

[7] O'Connor D, Ginzburg P, Rodríguez-Fortuño F J, et al. Spin-orbit coupling in surface plasmon scattering by nanostructures[J]. Nature Communications, 2014, 5: 5327.

[8] Dai H L, Yuan L Q, Yin C, et al. Direct visualizing the spin Hall effect of light via ultrahigh-order modes[J]. Physical Review Letters, 2020, 124(5): 053902.

[9] Berry M V. Optical currents[J]. Journal of Optics A: Pure and Applied Optics, 2009, 11(9): 094001.

[10] Bliokh K Y, Bekshaev A Y, Nori F. Extraordinary momentum and spin in evanescent waves[J]. Nature Communications, 2014, 5: 3300.

[11] Belinfante F J. On the current and the density of the electric charge, the energy, the linear momentum and the angular momentum of arbitrary fields[J]. Physica, 1940, 7(5): 449-474.

[12] Albaladejo S, Marqués M I, Laroche M, et al. Scattering forces from the curl of the spin angular momentum of a light field[J]. Physical Review Letters, 2009, 102(11): 113602.

[13] Bliokh K Y, Rodríguez-Fortuño F J, Nori F, et al. Spin-orbit interactions of light[J]. Nature Photonics, 2015, 9(12): 796-808.

[14] Van Mechelen T, Jacob Z. Universal spin-momentum locking of evanescent waves[J]. Optica, 2016, 3(2): 118-126.

[15] Abujetas D R, Sánchez-Gil J A. Spin angular momentum of guided light induced by transverse confinement and intrinsic helicity[J]. ACS Photonics, 2020, 7(2): 534-545.

[16] Bliokh K Y, Smirnova D, Nori F. Quantum spin Hall effect of light[J]. Science, 2015, 348(6242): 1448-1451.

[17] Shi P, Du L P, Li C C, et al. Transverse spin dynamics in structured electromagnetic guided waves[J]. Proceedings of the National Academy of Sciences of the United States of America, 2021, 118(6): 2018816118.

[18] Du L P, Yang A P, Zayats A V, et al. Deep-subwavelength features of photonic skyrmions in a confined electromagnetic field with orbital angular momentum[J]. Nature Physics, 2019, 15(7): 650-654.

[19] Lei X R, Yang A P, Shi P, et al. Photonic spin lattices: symmetry constraints for skyrmion and meron topologies[J]. Physical Review Letters, 2021, 127(23): 237403.

[20] Pancharatnam S. Generalized theory of interference, and its applications[J]. Proceedings of the Indian Academy of Sciences-Section A, 1956, 44(5): 247-262.

[21] Berry M V. Quantal phase factors accompanying adiabatic changes[J]. Proceedings of the Royal Society of London A Mathematical and Physical Sciences, 1984, 392(1802): 45-57.

[22] Onoda M, Murakami S, Nagaosa N. Hall effect of light[J]. Physical Review Letters, 2004, 93(8): 083901.

[23] Shitrit N, Bretner I, Gorodetski Y, et al. Optical spin Hall effects in plasmonic chains[J]. Nano Letters, 2011, 11(5): 2038-2042.

[24] Bliokh K Y, Bliokh Y P. Conservation of angular momentum, transverse shift, and spin Hall effect in reflection and refraction of an electromagnetic wave packet[J]. Physical Review Letters, 2006, 96(7): 073903.

[25] Bliokh K Y, Bliokh Y P. Polarization, transverse shifts, and angular momentum conservation laws in partial reflection and refraction of an electromagnetic wave packet[J]. Physical Review E, 2007, 75(6): 066609.

[26] Qin Y, Li Y, He H Y, et al. Measurement of spin Hall effect of reflected light[J]. Optics Letters, 2009, 34(17): 2551-2553.

[27] Hosten O, Kwiat P. Observation of the spin Hall effect of light via weak measurements[J]. Science, 2008, 319(5864): 787-790.

[28] Hermosa N, Nugrowati A M, Aiello A, et al. Spin Hall effect of light in metallic reflection[J]. Optics Letters, 2011, 36(16): 3200-3202.

[29] Zhu W G, Zheng H D, Zhong Y C, et al. Wave-vector-varying Pancharatnam-Berry phase photonic spin Hall effect[J]. Physical Review Letters, 2021, 126(8): 083901.

[30] Pan M M, Li Y, Ren J L, et al. Impact of in-plane spread of wave vectors on spin Hall effect of light around Brewster's angle[J]. Applied Physics Letters, 2013, 103(7): 071106.

[31] Ren J L, Wang B, Xiao Y F, et al. Direct observation of a resolvable spin separation in the spin Hall effect of light at an air-glass interface[J]. Applied Physics Letters, 2015, 107(11): 111105.

[32] Kong L J, Wang X L, Li S M, et al. Spin Hall effect of reflected light from an air-glass interface around the Brewster's angle[J]. Applied Physics Letters, 2012, 100(7): 071109.

[33] Luo H L, Zhou X X, Shu W X, et al. Enhanced and switchable spin Hall effect of light near the Brewster angle on reflection[J]. Physical Review A, 2011, 84(4): 043806.

[34] Ling X H, Zhou X X, Huang K, et al. Recent advances in the spin Hall effect of light[J]. Reports on Progress in Physics, 2017, 80(6): 066401.

[35] Kim M, Yang Y, Lee D, et al. Spin Hall effect of light: from fundamentals to recent advancements[J]. Laser & Photonics Reviews, 2023, 17(1): 2200046.

[36] Tomita A, Chiao R Y. Observation of Berry's topological phase by use of an optical fiber[J]. Physical Review Letters, 1986, 57(8): 937-940.

[37] Luo W J, Xiao S Y, He Q, et al. Photonic spin Hall effect with nearly 100% efficiency[J]. Advanced Optical Materials, 2015, 3(8): 1102-1108.

[38] Huang L L, Chen X Z, Mühlenbernd H, et al. Dispersionless

phase discontinuities for controlling light propagation[J]. Nano Letters, 2012, 12(11): 5750-5755.
[39] Bomzon Z, Kleiner V, Hasman E. Pancharatnam: Berry phase in space-variant polarization-state manipulations with subwavelength gratings[J]. Optics Letters, 2001, 26(18): 1424-1426.
[40] Ling X H, Zhou X X, Yi X N, et al. Giant photonic spin Hall effect in momentum space in a structured metamaterial with spatially varying birefringence[J]. Light: Science & Applications, 2015, 4(5): e290.
[41] Bomzon Z, Biener G, Kleiner V, et al. Space-variant Pancharatnam-Berry phase optical elements with computer-generated subwavelength gratings[J]. Optics Letters, 2002, 27(13): 1141-1143.
[42] Bomzon Z, Biener G, Kleiner V, et al. Radially and azimuthally polarized beams generated by space-variant dielectric subwavelength gratings[J]. Optics Letters, 2002, 27(5): 285-287.
[43] Cohen E, Larocque H, Bouchard F, et al. Geometric phase from Aharonov-Bohm to Pancharatnam-Berry and beyond[J]. Nature Reviews Physics, 2019, 1(7): 437-449.
[44] Yu N F, Genevet P, Kats M A, et al. Light propagation with phase discontinuities: generalized laws of reflection and refraction[J]. Science, 2011, 334(6054): 333-337.
[45] Yin X, Ye Z, Rho J, et al. Photonic spin Hall effect at metasurfaces[J]. Science, 2013, 339(6126): 1405-1407.
[46] Dong J W, Chen X D, Zhu H Y, et al. Valley photonic crystals for control of spin and topology[J]. Nature Materials, 2017, 16(3): 298-302.
[47] Guo C, Xiao M, Guo Y, et al. Meron spin textures in momentum space[J]. Physical Review Letters, 2020, 124(10): 106103.
[48] Zhen B, Hsu C W, Lu L, et al. Topological nature of optical bound states in the continuum[J]. Physical Review Letters, 2014, 113(25): 257401.
[49] Fan S H, Joannopoulos J D. Analysis of guided resonances in photonic crystal slabs[J]. Physical Review B, 2002, 65(23): 235112.
[50] Wang B, Liu W Z, Zhao M X, et al. Generating optical vortex beams by momentum-space polarization vortices centred at bound states in the continuum[J]. Nature Photonics, 2020, 14(10): 623-628.
[51] Liu W Z, Wang B, Zhang Y W, et al. Circularly polarized states spawning from bound states in the continuum[J]. Physical Review Letters, 2019, 123(11): 116104.
[52] Wang J J, Shi L, Zi J A. Spin Hall effect of light via momentum-space topological vortices around bound states in the continuum[J]. Physical Review Letters, 2022, 129(23): 236101.
[53] Wu L H, Hu X A. Scheme for achieving a topological photonic crystal by using dielectric material[J]. Physical Review Letters, 2015, 114(22): 223901.
[54] Barik S, Karasahin A, Flower C, et al. A topological quantum optics interface[J]. Science, 2018, 359(6376): 666-668.
[55] Kuznetsov A I, Miroshnichenko A E, Brongersma M L, et al. Optically resonant dielectric nanostructures[J]. Science, 2016, 354(6314): aag2472.
[56] Araneda G, Walser S, Colombe Y, et al. Wavelength-scale errors in optical localization due to spin-orbit coupling of light[J]. Nature Physics, 2019, 15(1): 17-21.
[57] Petersen J, Volz J, Rauschenbeutel A. Chiral nanophotonic waveguide interface based on spin-orbit interaction of light[J]. Science, 2014, 346(6205): 67-71.
[58] Bliokh K Y, Ostrovskaya E A, Alonso M A, et al. Spin-to-orbital angular momentum conversion in focusing, scattering, and imaging systems[J]. Optics Express, 2011, 19(27): 26132-26149.
[59] Liu J W, Yang Q A, Chen S Z, et al. Intrinsic optical spatial differentiation enabled quantum dark-field microscopy[J]. Physical Review Letters, 2022, 128(19): 193601.
[60] Neugebauer M, Banzer P, Nechayev S. Emission of circularly polarized light by a linear dipole[J]. Science Advances, 2019, 5(6): eaav7588.
[61] Rong K X, Wang B, Reuven A, et al. Photonic Rashba effect from quantum emitters mediated by a Berry-phase defective photonic crystal[J]. Nature Nanotechnology, 2020, 15(11): 927-933.
[62] Picardi M F, Zayats A V, Rodríguez-Fortuño F J. Janus and Huygens dipoles: near-field directionality beyond spin-momentum locking[J]. Physical Review Letters, 2018, 120(11): 117402.
[63] Rodríguez-Herrera O G, Lara D, Bliokh K Y, et al. Optical nanoprobing via spin-orbit interaction of light[J]. Physical Review Letters, 2010, 104(25): 253601.
[64] Ling X H, Guan F X, Cai X D, et al. Topology-induced phase transitions in spin-orbit photonics[J]. Laser & Photonics Reviews, 2021, 15(6): 2000492.
[65] Lin D M, Fan P Y, Hasman E, et al. Dielectric gradient metasurface optical elements[J]. Science, 2014, 345(6194): 298-302.
[66] Khorasaninejad M, Chen W T, Zhu A Y, et al. Multispectral chiral imaging with a metalens[J]. Nano Letters, 2016, 16(7): 4595-4600.
[67] Mun J, Kim M, Yang Y, et al. Electromagnetic chirality: from fundamentals to nontraditional chiroptical phenomena[J]. Light: Science & Applications, 2020, 9: 139.
[68] Wang B, Dong F L, Li Q T, et al. Visible-frequency dielectric metasurfaces for multiwavelength achromatic and highly dispersive holograms[J]. Nano Letters, 2016, 16(8): 5235-5240.
[69] Maguid E, Yulevich I, Yannai M, et al. Multifunctional interleaved geometric-phase dielectric metasurfaces[J]. Light: Science & Applications, 2017, 6(8): e17027.
[70] Maguid E, Yulevich I, Veksler D, et al. Photonic spin-controlled multifunctional shared-aperture antenna array[J]. Science, 2016, 352(6290): 1202-1206.
[71] Zhou X, Ling X, Luo H, et al. Identifying graphene layers via spin Hall effect of light[J]. Applied Physics Letters, 2012, 101(25): 251602.
[72] Sheng L J, Zhou X X, Zhong Y H, et al. Exotic photonic spin Hall effect from a chiral interface[J]. Laser & Photonics Reviews, 2023, 17(2): 2200534.
[73] Zhu T F, Lou Y J, Zhou Y H, et al. Generalized spatial differentiation from the spin Hall effect of light and its application in image processing of edge detection[J]. Physical Review Applied, 2019, 11(3): 034043.
[74] Wang R S, He S S, Luo H L. Photonic spin-hall differential microscopy[J]. Physical Review Applied, 2022, 18(4): 044016.
[75] Magallanes H, Brasselet E. Macroscopic direct observation of optical spin-dependent lateral forces and left-handed torques[J]. Nature Photonics, 2018, 12(8): 461-464.
[76] Li G X, Chen S M, Pholchai N, et al. Continuous control of the nonlinearity phase for harmonic generations[J]. Nature Materials, 2015, 14(6): 607-612.
[77] Stav T, Faerman A, Maguid E, et al. Quantum entanglement of the spin and orbital angular momentum of photons using metamaterials[J]. Science, 2018, 361(6407): 1101-1104.
[78] Solntsev A S, Agarwal G S, Kivshar Y S. Metasurfaces for quantum photonics[J]. Nature Photonics, 2021, 15(5): 327-336.
[79] Tang Y T, Li K, Zhang X C, et al. Harmonic spin-orbit angular momentum cascade in nonlinear optical crystals[J]. Nature Photonics, 2020, 14(11): 658-662.
[80] Shen Z, Dogariu A. Subradiant directional memory in cooperative scattering[J]. Nature Photonics, 2022, 16(2): 148-153.
[81] Yu S, Qiu C W, Chong Y D, et al. Engineered disorder in

photonics[J]. Nature Reviews Materials, 2021, 6(3): 226-243.
[82] Rotter S, Gigan S. Light fields in complex media: mesoscopic scattering meets wave control[J]. Reviews of Modern Physics, 2017, 89(1): 015005.
[83] Sheinfux H H, Lumer Y, Ankonina G, et al. Observation of Anderson localization in disordered nanophotonic structures[J]. Science, 2017, 356(6341): 953-956.
[84] Park J H, Park C, Yu H, et al. Subwavelength light focusing using random nanoparticles[J]. Nature Photonics, 2013, 7(6): 454-458.
[85] Xiong B, Liu Y, Xu Y H, et al. Breaking the limitation of polarization multiplexing in optical metasurfaces with engineered noise[J]. Science, 2023, 379(6629): 294-299.
[86] Maguid E, Yannai M, Faerman A, et al. Disorder-induced optical transition from spin Hall to random Rashba effect[J]. Science, 2017, 358(6369): 1411-1415.
[87] Bardon-brun T, Delande D, Cherroret N. Spin Hall effect of light in a random medium[J]. Physical Review Letters, 2019, 123(4): 043901.
[88] Rikken G L J A, van Tiggelen B A. Observation of magnetically induced transverse diffusion of light[J]. Nature, 1996, 381 (6577): 54-55.
[89] Nagaosa N, Tokura Y. Topological properties and dynamics of magnetic skyrmions[J]. Nature Nanotechnology, 2013, 8(12): 899-911.
[90] Bruno P, Dugaev V K, Taillefumier M. Topological Hall effect and Berry phase in magnetic nanostructures[J]. Physical Review Letters, 2004, 93(9): 096806.
[91] Verma N, Addison Z, Randeria M. Unified theory of the anomalous and topological Hall effects with phase-space Berry curvatures[J]. Science Advances, 2022, 8(45): eabq2765.
[92] Tsesses S, Cohen K, Ostrovsky E, et al. Spin-orbit interaction of light in plasmonic lattices[J]. Nano Letters, 2019, 19(6): 4010-4016.
[93] Karnieli A, Tsesses S, Bartal G, et al. Emulating spin transport with nonlinear optics, from high-order skyrmions to the topological Hall effect[J]. Nature Communications, 2021, 12: 1092.
[94] Wang B, Maguid E, Rong K X, et al. Photonic topological spin Hall effect mediated by vortex pairs[J]. Physical Review Letters, 2019, 123(26): 266101.
[95] Kosterlitz J M. The critical properties of the two-dimensional XY model[J]. Journal of Physics C: Solid State Physics, 1974, 7 (6): 1046-1060.
[96] van Tiggelen B A. Transverse diffusion of light in faraday-active media[J]. Physical Review Letters, 1995, 75(3): 422-424.
[97] Karpa L, Weitz M. A Stern-Gerlach experiment for slow light [J]. Nature Physics, 2006, 2(5): 332-335.
[98] Wang B, Rong K X, Maguid E, et al. Probing nanoscale fluctuation of ferromagnetic meta-atoms with a stochastic photonic spin Hall effect[J]. Nature Nanotechnology, 2020, 15 (6): 450-456.
[99] Wang J J, Li H, Ma Y T, et al. Routing valley exciton emission of a WS_2 monolayer via delocalized Bloch modes of in-plane inversion-symmetry-broken photonic crystal slabs[J]. Light: Science & Applications, 2020, 9: 148.
[100] Chen Y, Feng J G, Huang Y Q, et al. Compact spin-valley-locked perovskite emission[J]. Nature Materials, 2023: 1-6.
[101] Sun L Y, Wang C Y, Krasnok A, et al. Separation of valley excitons in a MoS_2 monolayer using a subwavelength asymmetric groove array[J]. Nature Photonics, 2019, 13(3): 180-184.
[102] Davis T J, Janoschka D, Dreher P, et al. Ultrafast vector imaging of plasmonic skyrmion dynamics with deep subwavelength resolution[J]. Science, 2020, 368(6489): eaba6415.
[103] Li G Z, Wang L J, Ye R, et al. Direct extraction of topological Zak phase with the synthetic dimension[J]. Light: Science & Applications, 2023, 12: 81.
[104] Yu D Y, Li G Z, Wang L J, et al. Moiré lattice in one-dimensional synthetic frequency dimension[J]. Physical Review Letters, 2023, 130(14): 143801.
[105] Yu D Y, Peng B, Chen X F, et al. Topological holographic quench dynamics in a synthetic frequency dimension[J]. Light: Science & Applications, 2021, 10: 209.
[106] Liu J, Su R B, Wei Y M, et al. A solid-state source of strongly entangled photon pairs with high brightness and indistinguishability[J]. Nature Nanotechnology, 2019, 14(6): 586-593.
[107] Skjærvø S H, Marrows C H, Stamps R L, et al. Advances in artificial spin ice[J]. Nature Reviews Physics, 2020, 2(1): 13-28.

Photonic Spin Hall Effect in Micro- and Nano-Optics

Feng Juan[1], Wang Bo[1*], Chen Xianfeng[1,2,3]

[1]*State Key Laboratory of Advanced Optical Communication Systems and Networks, School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai* 200240, *China*;

[2]*Shanghai Research Center for Quantum Sciences, Shanghai* 201315, *China*;

[3]*Collaborative Innovation Center of Light Manipulation and Applications, Shandong Normal University, Jinan* 250358, *Shandong, China*

Abstract

Significance Optical spin-orbit coupling is ubiquitous in nanoscale light-matter interactions. An in-depth study of these phenomena not only contributes to the discovery of new optical phenomena but also provides many opportunities for developing new technologies for light manipulation. In recent years, planar photonic devices such as geometric phase metasurfaces have shown many attractive applications, including multi-wavelength spin-dependent wavefront steering, spin-polarized photon generation, and spin-polarized thermal light emission. Most of these functions are achieved based on particularly designed nanostructures with certain types of spatial symmetry breaking, which aims to manipulate light in a

subwavelength resolution and spin bases. In comparison, the interactions between light and disordered micro- and nanostructures also begin to catch our attention. However, the inherent randomness of disordered structures has made the research on spin-orbit coupling effects quite challenging, as stochastic processes must be considered in a statistic manner. Particularly, the emerging photonic spin Hall effect in random systems has not yet been fully understood. For instance, even though random geometric phase fluctuations and random vortices can both induce a photonic spin Hall effect, they have distinct physics origins. Thus, the underlined physics of the photonic spin split effects from different disordered geometric phases remains to be explored. This paper introduces the basic concept of the spin of light and spin-orbit coupling phenomena in different micro- and nano-optical systems and then focuses on analyzing the spin split effects of two-dimensional random systems, including anisotropic disorder, magneto-optical fluctuations, vortices, and random dipole radiation. Meanwhile, we attempt to utilize the photonic spin Hall effect in disordered systems as a potential means to precisely detect and manipulate two-dimensional magnetic and thermodynamic systems for the sensing and control of phase transition phenomena.

Progress A typical result of optical spin-orbit coupling is the photonic spin Hall effect (PSHE), which describes the spatial split between light that carries opposite spins. For example, PSHE occurs when a polarized Gaussian beam is reflected or refracted at the air-dielectric material interface [Fig. 2(b)]. It also emerges when the propagation direction of a polarized paraxial light is slowly changing in free space, where the light polarization will rotate accordingly. In 2009, Bliokh *et al.* coupled a paraxial beam into a cylindrical glass and realized a spiral trajectory of light through continuous total internal reflections on the inner surface of the cylindrical glass. The separation of spin-up and spin-down components of light is gradually amplified by accumulating geometric phases during this progress, and a PSHE was finally observed. In 2015, it was also demonstrated that the spin-momentum locking in the evanescent wave exhibits an inherent quantum spin Hall effect of light, which is a unidirectional spin transfer phenomenon of light along the interface surface. Around 2001, Hasman′s group developed a set of planar geometric phase optical elements by spatially-varying subwavelength grating structures called Pancharatnam-Berry phase optical element [Fig. 2(d)], which is the earliest version of the geometric phase metasurfaces. Currently, geometric phase metasurfaces have been widely applied to construct versatile planar photonic devices for spin-based light manipulation and detection. Nonparaxial beams sometimes can behave counterintuitively. For instance, it has long been thought that linearly polarized dipole radiation does not carry angular momentum. However, recent theories and experiments have shown that the near-field of linear polarized dipole radiation can have a spin texture [Fig. 2(j)], and this nearfield spin information can be observed through waveguide coupling or scattering processes of isotropic nanoparticles. The interaction between light and disordered structures can produce novel phenomena and unpredictable results. For instance, disorders can be engineered to eliminate laser speckles for better wavefront shaping. In 2021, it has also been shown that, through the design of disordered noise, the information capacity limit of traditional metasurfaces can be broken, and wavefront control with more polarization degrees of freedom can be obtained. In 2017, Maguid *et al.* reported on photonic spin-symmetry breaking and unexpected spin-optical transport phenomena arising from subwavelength-scale disordered geometric phase structures. Weak disorder induces a photonic spin Hall effect, which is observed via quantum weak measurements, whereas strong disorder leads to random spin-split modes in momentum space, which is called a random optical Rashba effect. As the geometric phase of the metasurface to the spin of light has the same mechanism as the Berry phase, a similar spin Hall effect can be produced in principle. In 2019, Wang *et al.* observed photonic topological defects of bound vortex pairs and unbound vortices generated from a two-dimensional array of nanoantennas, which is achieved by randomly inserting local deformations in the metasurfaces. The spin Hall effect of light is established based on discrete topological structures, or subwavelength vortex and antivortex pairs. Light does not carry an electric charge and therefore does not directly interact with the magnetic field, but a magnetized medium does affect the light propagation path. In 2020, Wang *et al.* studied a stochastic photonic spin Hall effect arising from space-variant Berry-Zak phases, which are generated by disordered magneto-optical effects. This spin shift is observed from a spatially bounded lattice of ferromagnetic meta-atoms displaying nanoscale disorders. A random variation of the radii of the meta-atoms induces the nanoscale fluctuation. This spin separation of light is in analogy to a Stern-Gerlach experiment, and photons of opposite spin are deflected into opposite directions as they interact with a magnetic material with random spatial gradients. The luminescence of quantum dots, 2D semiconductor materials, perovskite particles, and some atoms or molecules can be considered as dipole radiation randomly generated in time and space. Efficient polarization and phase control of this kind of radiation requires novel metasurfaces that have strong mode coupling between nanostructures. To achieve efficient control of randomly radiated dipoles [Fig. 11(d)], Rong *et al.* designed a geometric phase defective photonic crystal. The insertion of geometric phase structures into a photonic crystal that has a bandgap realizes many local defect modes. These defect modes not only achieve localized light emission but also select radiation polarization. Via tight-binding coupling between nanoantennas, the light emitted by each dipole can propagate to neighboring nanostructures to obtain a geometric phase accumulation that radiates into space with a predesigned spin-dependent momentum [Fig. 11(c)]. This configuration realizes efficiency polarization and momentum control of the light from random emitters.

Conclusions and Prospects As we have witnessed over the past two decades, optical spin-orbit coupling is ubiquitous in many optical systems. An in-depth understanding of these phenomena not only contributes to basic physics understanding but also brings forth a diversity of applications. Nowadays, the development of nano-photonics enters a stage where higher information dimensionality, higher spatial-time resolution, and many other extreme conditions are required. One promising direction is utilizing high-quality factor metasurfaces that can manipulate the polarization and wavefront of light beyond lasers, such as thermal light and quantum emitters. The other direction is to combine spin-optics and nano-magnetism. In particular, magnetic phenomena, such as those in magnetic metasurfaces or artificial spin ice, can be potentially detected by PSHE and quantum weak measurement. Finally, an optical means is provided to detect and manipulate the magnetic ordering and phase transition in correlated physical systems.

Key words photonic spin; metasurface; random phenomenon; optical vortex; geometric phase