第 50 卷 第 18 期/2023 年 9 月/中国激光 特邀综述

液晶的多维度光场调控技术研究进展

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摘要 液晶作为一种介于液态与结晶态之间的功能性软材料，可以同时表现出液体流动性和晶体的各向异性，被广泛应用于图像显示、集成光电子学、光通信等领域。近年来，由于液晶理论研究的深入及其加工技术的发展，液晶在几何相位、动态可调谐等光场调控方面的优势推动了光学器件的平面化、集成化、智能化和小型化。综述了液晶在光场调控方面的最新应用进展，具体讨论了其对光波振幅、相位、偏振等多维度参数的调控特性，进而探讨了液晶在多功能光学器件和光学加密系统中的应用。

关键词 光数据存储；液晶；光场调控；各向异性；几何相位；多功能；光学加密

中图分类号 O438 **文献标志码** A **DOI：** 10.3788/CJL230716

1 引 言

液晶是一种介于液体与晶体之间的物质，同时表现出液体流动性和晶体的各向异性[1-2]，由于其优异的光电特性而被广泛应用于平板显示领域，如手机、计算机、液晶电视等。随着液晶理论研究的深入和加工技术的不断发展，液晶对于实现集成化、智能化和小型化的光学系统具有越来越重要的意义。近年来，研究人员利用液晶对偏振、振幅、相位等多维参数进行调控，构建了一系列平面功能型液晶器件，如聚焦透镜、螺旋相位板、光栅、光束转向器等[3-6]，如图 1 所示。同时，液晶在外部电场、磁场、温度、压力等作用下，会发生分子排列方式的改变，从而导致光学特性的变化，这使得液晶具有出色的动态调控性能[7-10]。动态可调谐液晶器件具有波段宽、可开关、响应速度快等特点，目前已被广泛应用于调焦系统、切换显示等领域。

液晶有着丰富的相态，包括近晶相、向列相、胆甾相、蓝相等。对于近晶相液晶（SLC），其液晶分子长轴相互平行，呈层状结构，分子在每一层内容易流动，但难以在层间移动，如图 2（a）所示。目前，关于近晶相液晶的研究以理论研究为主，比如电场和流体模型等[11-12]。对于向列相液晶（NLC），其液晶分子沿着长轴方向排列且绕着长轴旋转，液晶分子间的相对位置不固定，表现出相对较好的流动性，如图 2（b）所示。向列相液晶被广泛应用于显示面板、可调谐光学器件等方面[13-16]。对于胆甾相液晶（CLC），其液晶分子具有分层特性，每一层分子的指向一致，但相邻层之间存在一定的夹角，整体上呈螺旋结构，如图 2（c）所示。由于胆甾相液晶具有固有的自组织螺旋结构[17]，当与其螺旋结构方向相同的圆偏振光经过该结构时，圆偏振光就会发生反射并带有调控相位；而当与其螺旋结构方向相反的圆偏振光经过该结构时，圆偏振光就会发生透射并且不带有调控相位，这种圆偏振选择特性使胆甾相液晶常被用于起偏器、圆偏振转换器、反射式液晶显示器和传感器等领域[18-23]。对于蓝相液晶（BPLC），其形态特征介于各向同性相和胆甾相液晶之间，具有独特的双扭曲螺旋柱结构，如图 2（d）所示。这样的排列赋予蓝相液晶特殊的性质，例如光学各向同性、克尔效应诱导的双折射特性、快速电场响应特性等[24-25]。

本文首先从液晶的双折射特性入手，基于琼斯矩阵推导了液晶调控光波振幅和相位等的特性。随后讨论了摩擦取向、光控取向等液晶取向技术的发展，介绍了几种常见的光控取向技术。然后从液晶振幅调控器件、液晶相位调控器件、液晶复振幅调控器件、液晶-超表面动态调控器件四个方面，详细地讨论了基于液晶器件的多维度光场调控的最新研究进展和应用，并且讨论了相应器件在光学加密系统中的应用。

收稿日期： 2023-04-12；**修回日期：** 2023-05-09；**录用日期：** 2023-05-26；**网络首发日期：** 2023-06-05

基金项目： 国家自然科学基金（62275077，61905073）、广东省基础与应用基础研究基金（2023A1515011538）

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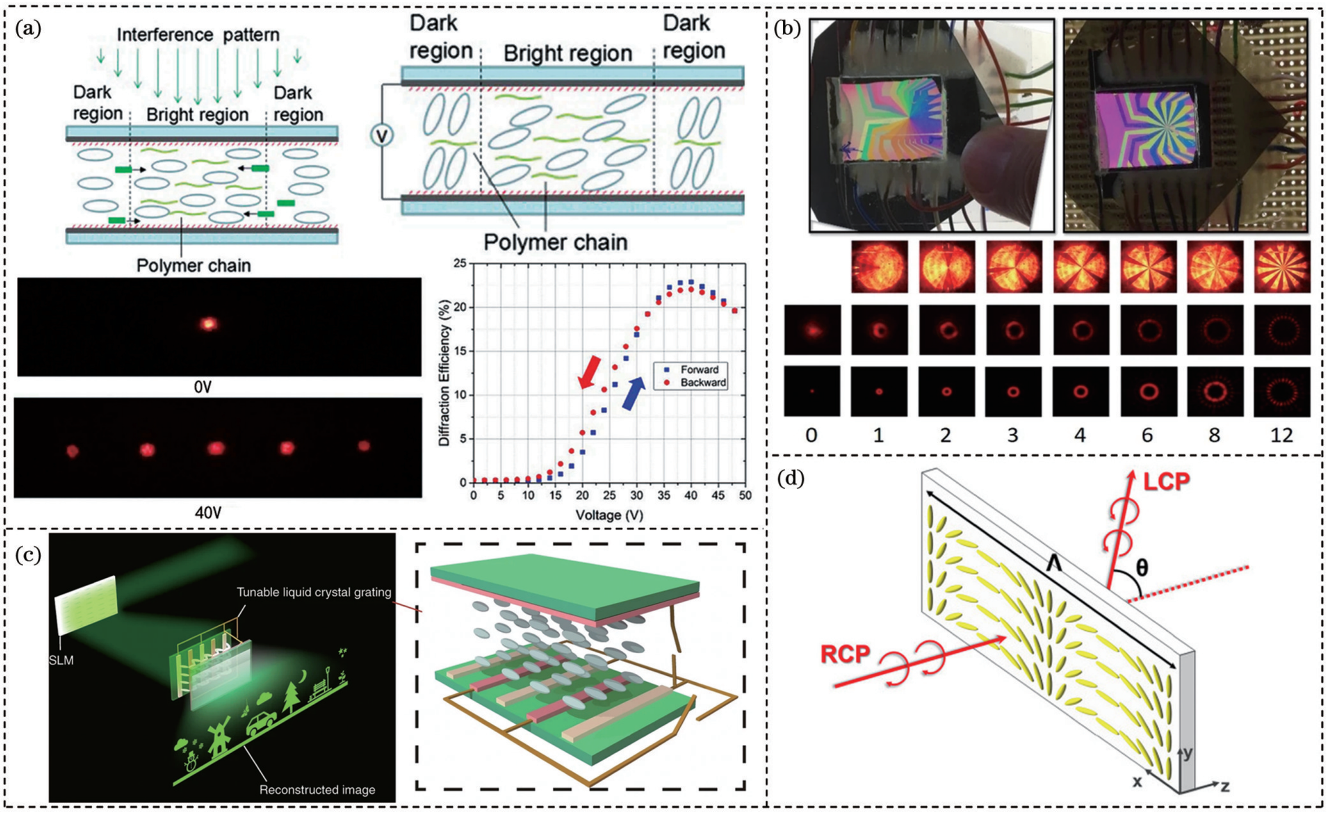

图1 平面功能性液晶器件。(a)菲涅耳液晶透镜[3]；(b)液晶螺旋相位板[4]；(c)可调谐液晶光栅[5]；(d)液晶红外光束转向器[6]

Fig. 1 Planar functional liquid crystal devices. (a) Fresnel liquid crystal lens[3]; (b) liquid crystal spiral phase plate[4]; (c) tunable liquid crystal grating[5]; (d) liquid crystal beam steering device[6]

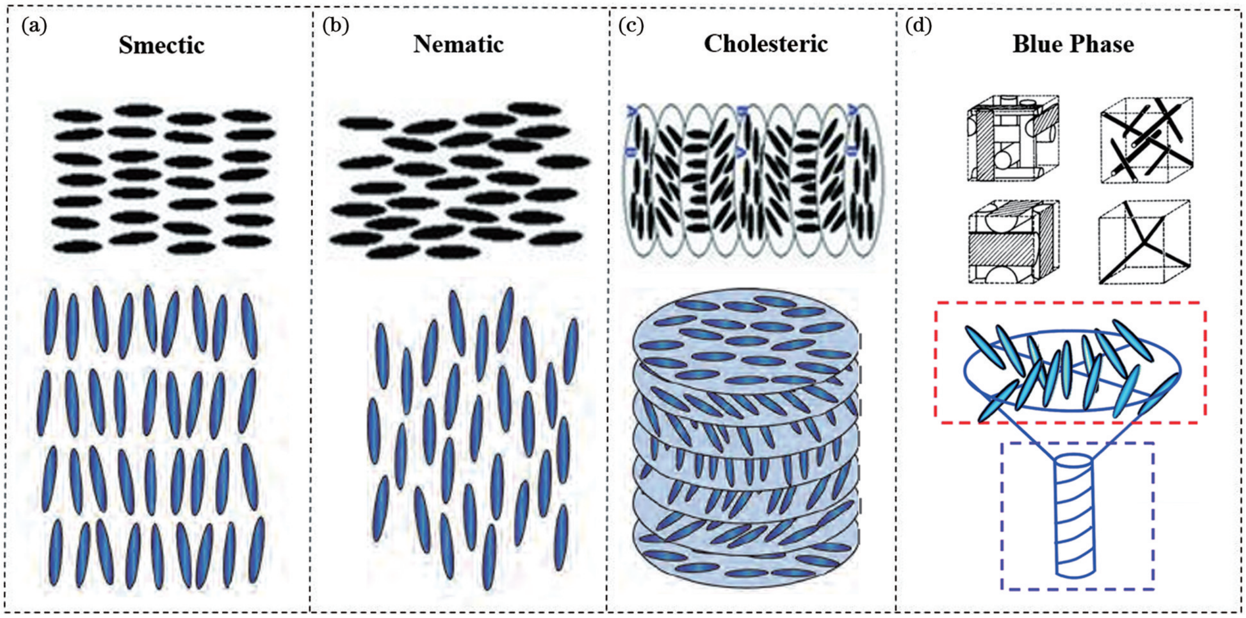

图2 液晶分子排列示意图。(a)近晶相液晶[26]；(b)向列相液晶[26]；(c)胆甾相液晶[26]；(d)蓝相液晶[24]

Fig. 2 Schematics of liquid crystal molecule arrangement. (a) Smectic liquid crystal[26]; (b) nematic liquid crystals[26]; (c) cholesteric liquid crystal[26]; (d) blue phase liquid crystal[24]

2 液晶的光场调控特性

2.1 双折射特性

如图3(a)所示，液晶分子呈细长棒状，由于结构的不对称性，长轴和短轴方向分别呈现两个不同的介电常数，即$\varepsilon_{\parallel}$和$\varepsilon_{\perp}$[27]。当$\Delta\varepsilon=\varepsilon_{\parallel}-\varepsilon_{\perp}>0$时，此类型的液晶材料定义为正性液晶，而当$\Delta\varepsilon<0$时，则定义为负性液晶。在光学性质方面，当入射光的偏振方向

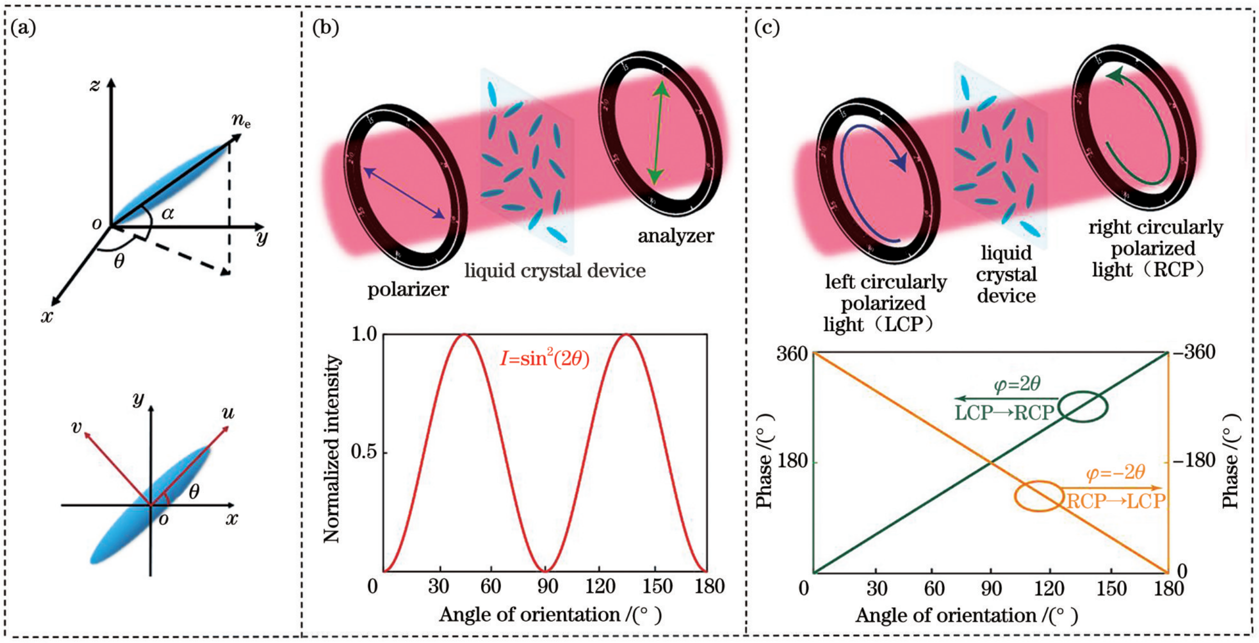

图 3 液晶分子调控机理。(a)液晶分子的结构示意图；(b)液晶的振幅调控特性；(c)液晶的几何相位调控特性

Fig. 3 Molecular modulation mechanism of liquid crystal. (a) Structural diagram of liquid crystal molecular; (b) amplitude modulation properties of liquid crystals; (c) geometric phase modulation properties of liquid crystals

平行于液晶光轴方向时，液晶材料的折射率为 n_e；而当入射光的偏振方向垂直于光轴方向时，折射率为 n_o。双折射率即两个折射率的差值为

$$\Delta n = n_e - n_o。 \tag{1}$$

当液晶分子与 xy 平面存在夹角即面外倾斜角（α）时，此时的等效双折射率（Δn_{eff}）为

$$\Delta n_{\mathrm{eff}} = n_{\mathrm{eeff}} - n_o = \frac{n_e n_o}{\sqrt{n_e^2 \sin^2\alpha + n_o^2 \cos^2\alpha}} - n_o, \tag{2}$$

式中：n_{eeff} 表示等效的液晶材料的折射率。此时，光透过液晶后的光程差（Γ）为

$$\Gamma = \frac{2\pi \Delta n_{\mathrm{eff}} d}{\lambda}, \tag{3}$$

式中：d 为液晶材料的厚度；λ 为光的波长。面外倾斜角 α 的变化会导致光程差、透射率等参数变化，这是液晶显示器振幅调控的原理。在液晶两端施加电压并且配合线偏振片，最终可产生不同的透射振幅。

2.2 振幅调控

通过控制液晶的面内取向角（θ）也可以实现输出光场的连续调控，我们可以利用琼斯矩阵来推导图 3(a)中液晶分子的振幅调控特性，在沿 x 轴方向传输的线偏振光通过液晶分子后，假设面外倾斜角 α 取 0，输出光场可表示为

$$\begin{bmatrix} E_{xo} \\ E_{yo} \end{bmatrix} = \boldsymbol{J}_{xy} \begin{bmatrix} E_{xi} \\ E_{yi} \end{bmatrix} = \boldsymbol{J}_{xy} \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \tag{4}$$

式中：E_{xi} 和 E_{yi} 分别为入射光的 x 偏振分量和 y 偏振分量；E_{xo} 和 E_{yo} 分别为出射光的 x 偏振分量和 y 偏振分量；$\boldsymbol{J}_{xy}$ 为琼斯矩阵，其表达式为

$$\boldsymbol{J}_{xy} = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \boldsymbol{J}_{uv} \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}, \tag{5}$$

式中：θ 表示面内取向角，即液晶分子在 xy 面上的投影与 x 轴之间的夹角；$\boldsymbol{J}_{uv}$ 可以表示成

$$\boldsymbol{J}_{uv} = \begin{bmatrix} t_u & 0 \\ 0 & t_v \end{bmatrix}, \tag{6}$$

式中：t_u 和 t_v 是沿液晶分子长短轴（u 轴和 v 轴）的透射系数。式(4)可以写成

$$\begin{bmatrix} E_{xo} \\ E_{yo} \end{bmatrix} = \boldsymbol{J}_{xy} \begin{bmatrix} E_{xi} \\ E_{yi} \end{bmatrix} = \boldsymbol{J}_{xy} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} t_u \cos^2\theta + t_v \sin^2\theta \\ (t_u - t_v)\sin\theta\cos\theta \end{bmatrix}。 \tag{7}$$

从式(7)可以看出，出射光中除了与入射偏振态相同的分量之外，还存在正交偏振的分量 E_{yo}。E_{yo} 的归一化强度（I）满足 $I=\sin^2(2\theta)$，如图 3(b)所示。这时可以利用液晶分子面内取向角的连续变化来连续调控振幅。

2.3 几何相位调控

几何相位是伴随圆偏振翻转过程出现的相位类型，可以通过旋转液晶面内取向角来实现精确调控。几何相位是 Berry 等[28-30]提出的，又称为 Pancharatnam-Berry（PB）相位。下面根据琼斯矩阵研究几何相位调控。当圆偏振光通过液晶分子后，输出光场表达式为

$$\begin{bmatrix} E_{xo} \\ E_{yo} \end{bmatrix} = \frac{\boldsymbol{J}_{xy}}{\sqrt{2}} \begin{bmatrix} 1 \\ \mathrm{i}\sigma \end{bmatrix} = \frac{1}{2\sqrt{2}} \left\{ (t_u + t_v) \begin{bmatrix} 1 \\ \mathrm{i}\sigma \end{bmatrix} + (t_u - t_v) \mathrm{e}^{\mathrm{i}2\sigma\theta} \begin{bmatrix} 1 \\ -\mathrm{i}\sigma \end{bmatrix} \right\}, \tag{8}$$

式中：$\sigma = \pm 1$，分别对应右旋圆偏振态和左旋圆偏振态。由式(8)可以得到，输出光场由两部分组成：前者振幅为 $(t_u + t_v)/2\sqrt{2}$，其偏振态与入射偏振态相同；后者振幅为 $(t_u - t_v)/2\sqrt{2}$，其偏振态与入射偏振态正交，且额外携带了 $2\sigma\theta$ 的几何相位（φ）。因此，在圆偏

振光的入射下，通过改变液晶取向角就能实现对光波相位的连续调控，如图 3(c)所示。另外，在液晶加工过程中，改变液晶层的厚度，使半波条件 $t_u = -t_v = 1$ 得到满足时，偏振转换效率可达 100%。

3 液晶取向技术发展

液晶取向技术主要有摩擦取向、倾斜蒸镀取向和光控取向等技术[31-35]，各项技术在不同的应用场合有其独特的优势。例如，工业上常用摩擦取向技术进行液晶取向层的加工，这种方法具有操作简单、成本低、稳定性高、可靠性好等优点，但也存在一些问题，如摩擦过程中基材表面容易产生缺陷、静电以及弯曲不规则的基材难以取向等。随着材料学的发展，光控取向剂的研发促进了液晶光控取向技术的发展，这种技术具有非接触、高分辨、图案化、可编程、高效率等特点，为液晶光子学和集成光电子学等前沿领域的发展奠定了基础。

目前液晶光控取向技术主要分为掩模版曝光系统、干涉曝光系统、直写曝光系统、等离激元掩模版曝光系统、动态掩模曝光系统等[36-41]。掩模版曝光系统是将掩模版放置在衬底的合适位置，再使用一定偏振方向的光进行取向处理，被取向光照射的部分材料记录下了光的偏振信息，而未被照射部分保持原样，如图 4(a)所示[40]。干涉曝光系统利用两束光的干涉光场进行曝光，从而实现取向层的精确取向，如图 4(b)所示[39]。直写曝光系统利用激光束连续扫描聚焦的方法对液晶器件进行加工，在激光束的配合下，将图案化的相位剖面以逐点加工的方式记录在取向层中，如图 4(c)所示[37]。数字微镜器件(DMD)动态掩模曝光系统是基于 DMD 设计的，其中 DMD 由许多像素化的微反射镜组成，它的作用相当于一个可以定制的掩模版，可以通过软件决定每个反射镜的工作状态，在电动

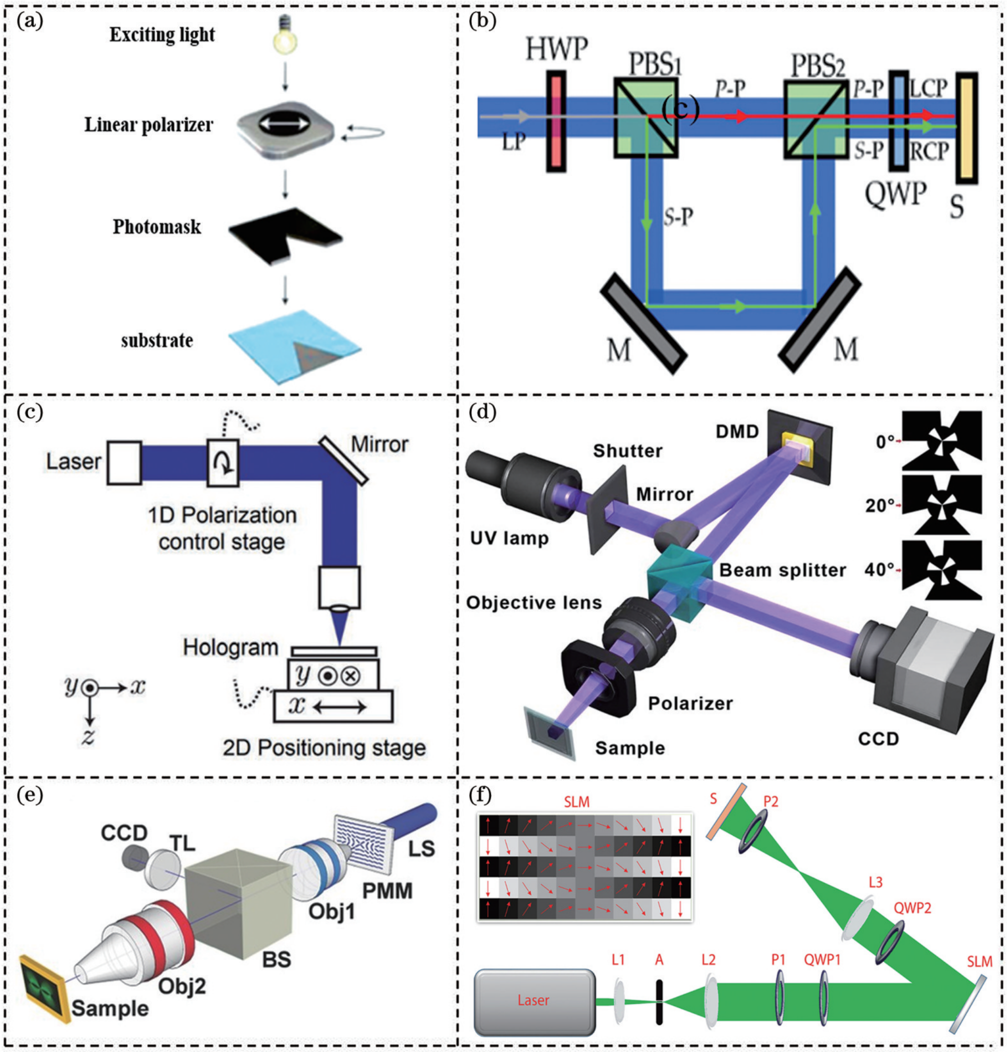

图 4 各种光取向技术系统。(a)掩模版曝光系统[40]；(b)干涉曝光系统[39]；(c)直写曝光系统[37]；(d)DMD 动态掩模曝光系统[38]；(e)等离激元掩模版曝光系统[41]；(f)SLM 动态掩模曝光系统[36]

Fig. 4 Various optical orientation technology systems. (a) Mask exposure system[40]; (b) interference exposure system[39]; (c) direct write exposure system[37]; (d) DMD dynamic mask exposure system[38]; (e) plasmon mask exposure system[41]; (f) SLM dynamic mask exposure system[36]

旋转线起偏器的配合下，将带有偏振信息的像素化图案转移至取向层中以完成取向，如图 4(d)所示[38]。等离激元掩模版曝光系统主要由具有特定偏振方向空间图案的等离激元掩模版构成，当光照亮等离激元掩模版后，带有特定偏振方向的透射光会诱导液晶分子发生空间取向，从而实现任意需要的二维和三维液晶分子取向，如图 4(e)所示[41]。基于空间光调制器(SLM)的动态掩模曝光系统则实现了单次曝光的光图案化，该系统主要通过外部电压单独控制 SLM 每个像素的排布，将带有偏振信息的像素化图案转移至取向层中以完成取向，如图 4(f)所示[36]。

4　液晶器件及其应用

4.1　振幅型液晶器件

4.1.1　液晶显示器

液晶振幅调控最广泛的应用便是液晶显示器[42-45]。液晶显示器最常见的类型之一是扭曲向列(TN)型显示器[43]。以 TN 型显示器为例，如图 5(a)所示，在玻璃基板中间放入液晶层，通过外加电场控制液晶分子的倾斜角(α)，从而控制出射光的偏振方向，进而控制显示屏展现出明暗的效果；在上偏振片与液晶层之间加入彩色滤光片，显示屏就会显示不同亮度的颜色。TN 型液晶显示器具有价格低廉、易于制造等优点，是很受欢迎的消费电子产品。20 世纪 80 年代，随着薄膜晶体管(TFT)技术的出现[46]，液晶显示器由手表等简单器件向更复杂的器件发展。20 世纪 90 年代，随着硅基液晶(LCOS)技术的发展[47]，采用互补金属氧化物半导体(CMOS)技术，可在硅基片上直接制作液晶显示器的驱动面板，实现了更高分辨率的显示。目前，液晶显示器已成为主流显示器件，具有工业化成熟、性价比高、节能、可视面积大等优点，被广泛应用于电脑、电视、手机等领域[44-45]。

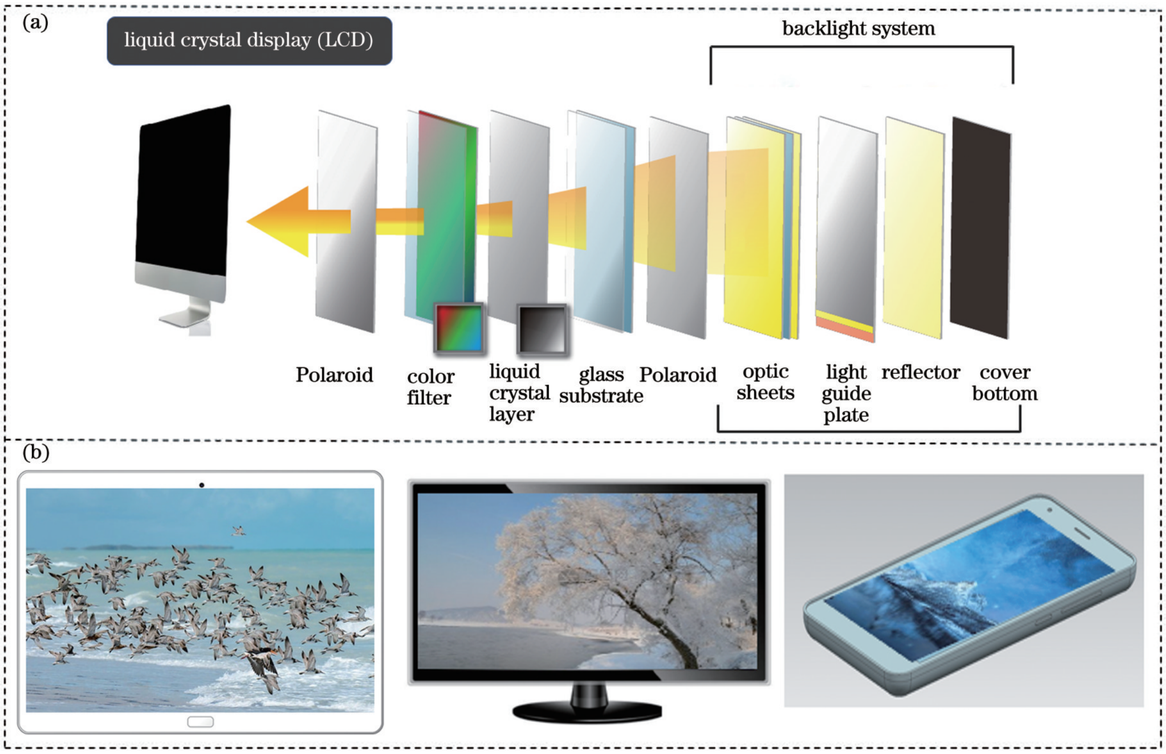

图 5　液晶显示器的原理与应用。(a)液晶显示器的结构示意图；(b)液晶显示器的应用

Fig. 5　Principle and applications of liquid crystal display. (a) Structural diagram of liquid crystal display; (b) applications of liquid crystal display

4.1.2　振幅型空间光调制器

振幅型空间光调制器由一系列独立的单元组成，可以通过控制这些单元来实现光波的振幅调控，其调控机理与液晶显示器相似，也是在液晶盒两端施加一定外电压，使液晶分子发生倾斜，即液晶分子的面外倾斜角 α 发生变化，进而透过液晶盒的线偏光的偏振态发生改变，线偏光的偏振方向与检偏器的偏振方向不再平行，出射光强也相应发生变化，如图 6(a)所示[48]。2010 年，Liang 等[49]基于振幅型空间光调制器等装置实现了高精度的激光光束整形，如图 6(b)所示。2018 年，Dorrah 等[50]提出了一种基于振幅型空间光调制器的折射率测试方法，根据光束强度曲线与介质折射率的特性，验证了在非常宽的折射率范围内可高灵敏度、高分辨率地测量折射率，如图 6(c)所示。基于液晶的振幅型空间光调制器具有振幅连续可调、调制精细等特点，在显示、光信息处理、光学传感器、光学制作等领域中都有很重要的应用[49-56]。

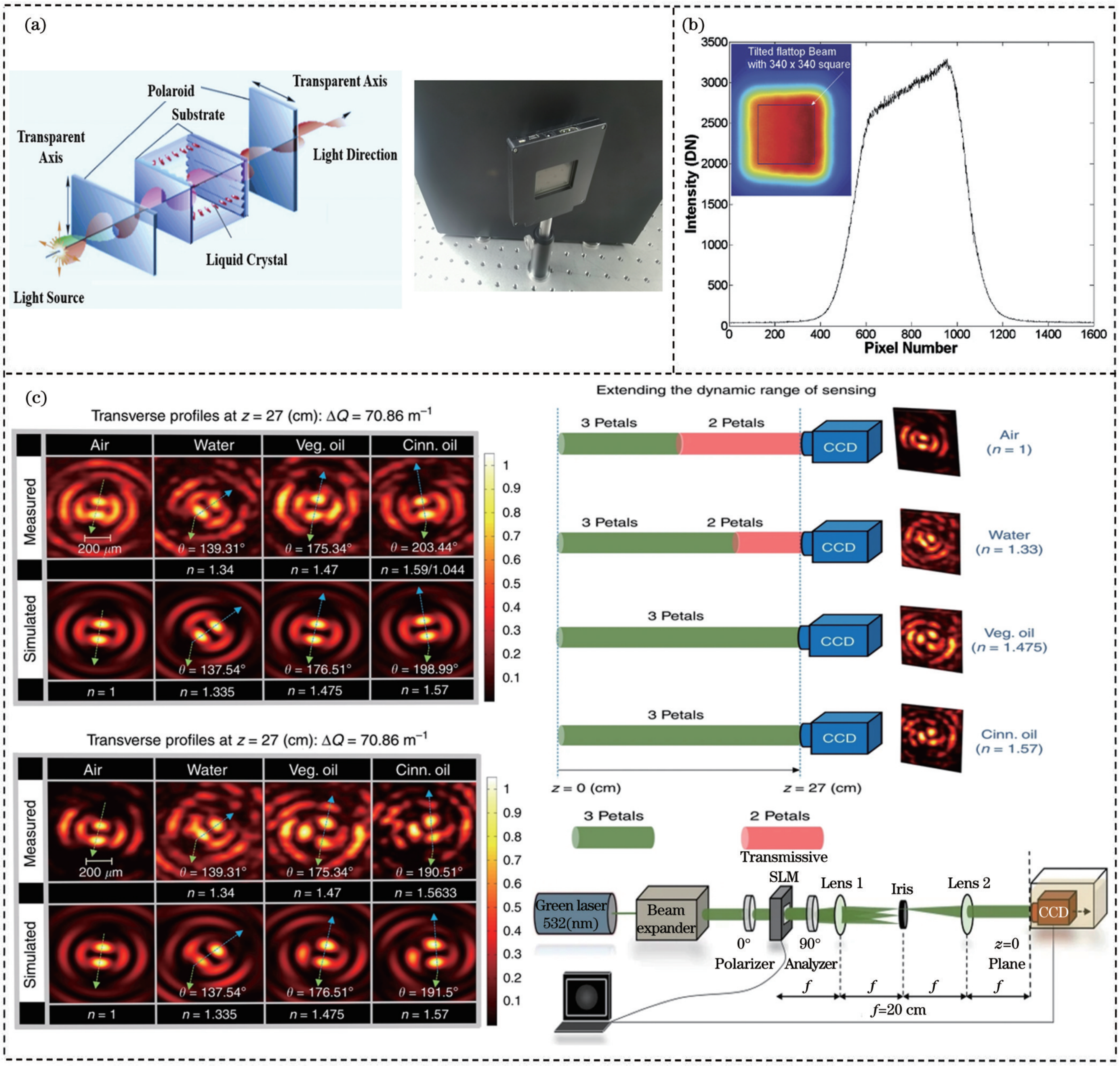

图 6　振幅型空间光调制器原理及应用。(a)Holoeye LC2012 振幅型空间光调制器及其原理[48]；(b)利用空间光调制器实现激光光束整形[49]；(c)基于空间光调制器测试折射率的可调折光仪示意图[50]

Fig. 6　Principle and applications of amplitude type spatial light modulator. (a) Holoeye LC2012 amplitude type spatial light modulator and its principle[48]; (b) laser beam shaping realized by using space light modulator[49]; (c) schematic of adjustable refraction instrument for measuring refractive index based on spatial light modulator[50]

4.1.3　液晶智能窗

液晶智能窗是一种基于液晶振幅调控技术的智能建筑材料，它可以通过控制液晶分子的取向和排列方式，调节窗户的透明度和反射率[57-59]。2017 年，Wang 等[60]设计了一种基于液晶-石墨烯复合材料的智能窗系统，该系统可以利用多种外部刺激改变智能窗的光学透明度，如图 7(a)所示。该系统通过施加电场来动态控制光透过窗户的透明度，同时对多种环境因素作出反应，在建筑和汽车中具有巨大的应用潜力。但这一方法也存在一些问题，例如加工不易、复合材料可扩展性低、不够稳定等。为了解决这些问题，2020 年，Hu 等[61]利用聚合物液晶制造了一种稳定的、可扩展的聚合物稳定液晶窗，基于外加电场液晶窗可以实现透明状态到不透明状态的转变，耐用性测试结果表明该光学器件在开关 10 万次的情况下不会出现光学对比度的下降，表现出很高的稳定性，如图 7(b)所示。液晶智能窗利用液晶材料来调节光透过率和热传递性能，可以实现快速、精确的智能调节，并且能够大幅降低能耗和制造成本。

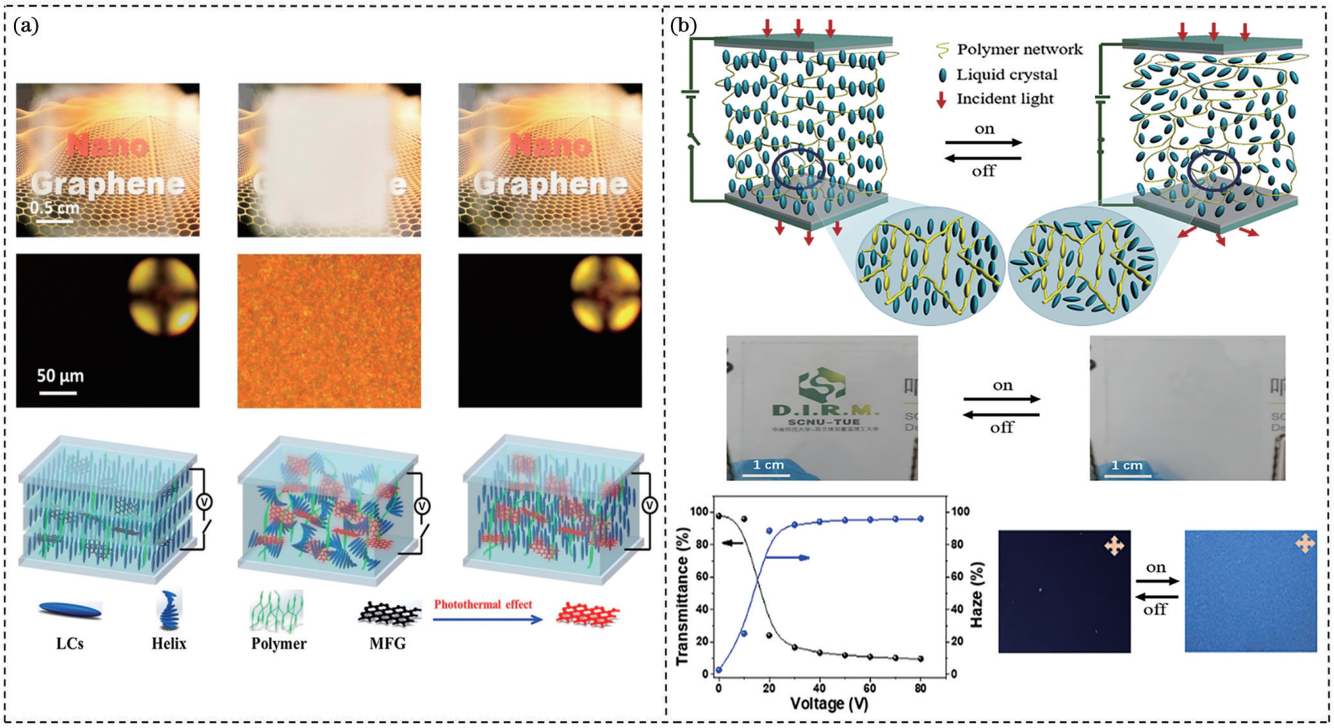

图 7　基于液晶的智能窗。(a)基于液晶/石墨烯复合材料的智能窗示意图[60];(b)基于聚合物材料液晶的稳定可扩展的智能窗示意图[61]

Fig. 7　Smart windows based on liquid crystal. (a) Schematic of smart window based on liquid crystal/graphene composites[60]; (b) schematic of stable and expandable smart window based on polymer material liquid crystal[61]

4.2　相位型液晶器件

4.2.1　相位型空间光调制器

相位型空间光调制器主要通过控制传输相位来调控入射光的相位[62-63]。如图 8(a)所示,根据液晶的双折射特性,相位型液晶空间光调制器在两个偏振片 P1 和 P2 的配合下工作,两个偏振片的偏振方向与竖直方向的夹角分别为 φ_1 和 φ_2,若在两个电极之间施加垂直于液晶层的电压,液晶分子的倾斜角 α 会随电场强度的变化而改变,进而 o 光和 e 光的相位延迟发生变化,因此通过控制液晶层两端的驱动电压可实现液晶传输相位的调控。2021 年,Zuo 等[64]使用相位型空间光调制器设计了一个基于线性空间傅里叶光学和非线性激活函数的可扩展性全光神经网络,并且该网络的非线性与线性变换误差是相互独立的,如图 8(b)所示。2023 年,Li 等[65]利用相位型空间光调制器和超表面构建了光学加密系统,只能通过结合空间光调制器和超表面变换的密文才能解码隐藏信息,这使得加密的信息具有较高的保密性,同时还设计了一个防伪标签以保证信息的真实性,如图 8(c)所示。

2020 年,Fang 等[66]将光学轨道角动量(OAM)作为全息信息载体,提出了全新的 OAM 全息技术,设计了基于空间光调制器的轨道角动量全息加密系统,如图 9(a)所示。由于 OAM 守恒,只有具有对应反向螺旋相位的 OAM 光束才能实现目标全息图的再现。因此,可以通过编码叠加不同 OAM 通道中的全息图,实现具有高安全度的光学加密技术。然而,目前的光学加密技术存在的问题是:密文与明文是线性关系,导致人们有可能通过解决一组线性方程,只用同一台加密机的两个密文就能破解系统。为了解决这一问题,2022 年,Hou 等[67]利用光折变晶体的相位调控效应,结合空间光调制器的动态调控功能,设计了一种非线性光学图像动态加密系统,如图 9(b)所示。他们在两个相位型空间光调制器上显示了两个独立的随机相位,在晶体上添加电压产生的图像作为密文,随后利用密钥解密密文,得到的图像与未加密前的图像相似,这为非线性光学领域的加密开辟了一条新途径。因此,基于相位型空间光调制器,可以实现对光相位的分区域调控,这使得相位型空间光调制器在全息成像、光学加密等领域中具有广阔的应用前景。

4.2.2　几何相位器件

液晶的几何相位器件主要是基于几何相位的宽带相位调制和液晶的低耗损高偏振转换效率来调控光场。2016 年,Duan 等[68]基于几何相位通过光取向技术制备了一个双频液晶偏振光栅,并验证了其作为光学开关的作用,如图 10(a)所示。除此之外,基于几何相位的液晶超薄透镜近年来也受到了广泛的关注。2017 年,Lin 等[69]基于几何相位调控的特点,设计了一种偏振切换型液晶透镜,如图 10(b)所示。2020 年,Zhou 等[70]基于几何相位设计了一种液晶双焦透镜,如图 10(c)所示,该透镜设计方案克服了以往双焦点透镜设计方法复杂等缺点。对于上述基于几何相位设计的透射式的向列相液晶,须通过调谐

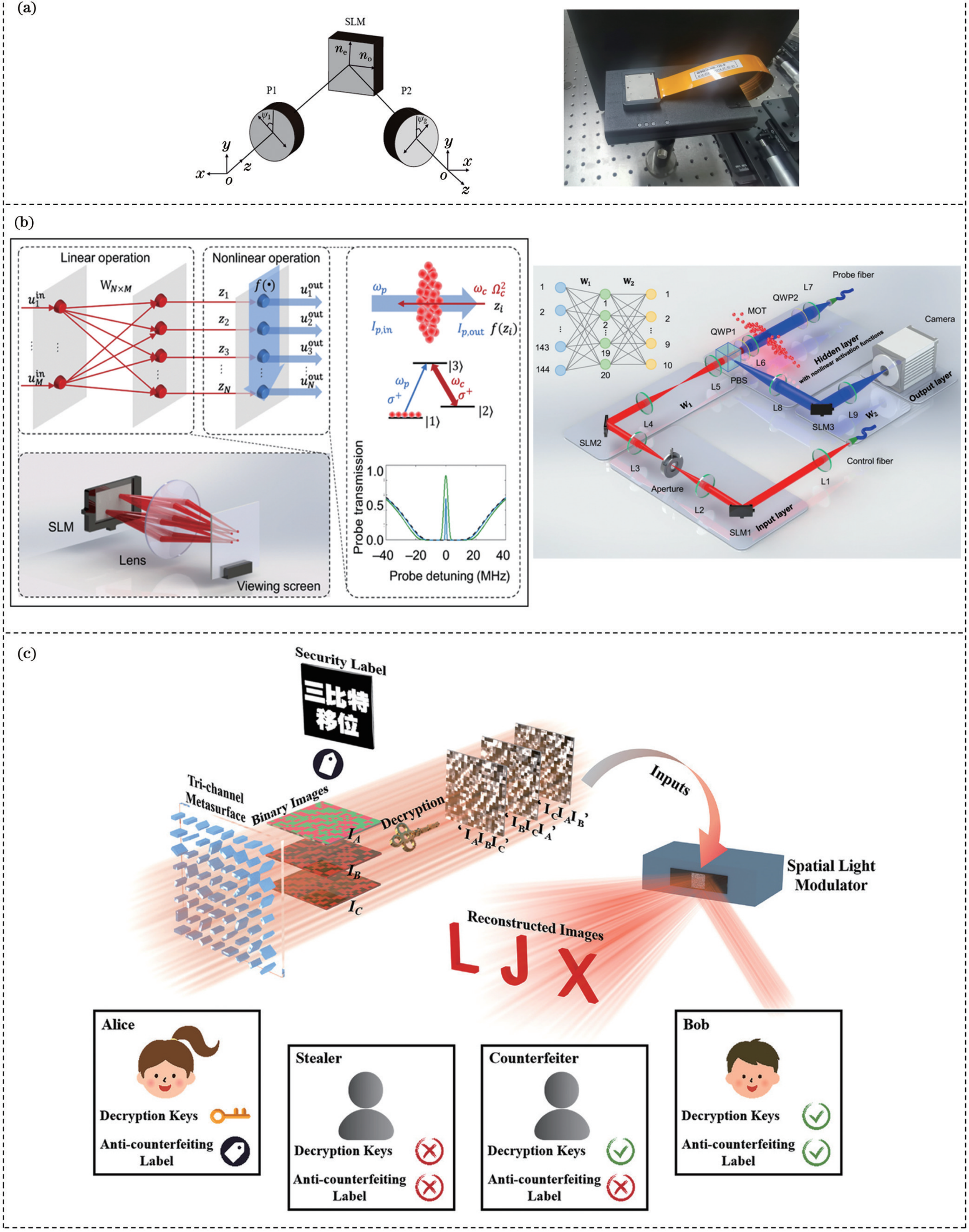

图 8 相位型空间光调制器原理及应用。(a)Holoeye PLUTO-2 相位型空间光调制器示意图及其原理;(b)基于空间光调制器的可扩展性全光神经网络[64];(c)基于相位型空间光调制器的加密系统[65]

Fig. 8 Principle and applications of phase type spatial light modulator. (a) Holoeye PLUTO-2 phase type spatial light modulator and its principle; (b) scalable all-optical neural network based on spatial optical modulator[64]; (c) encryption system based on phase type spatial light modulator[65]

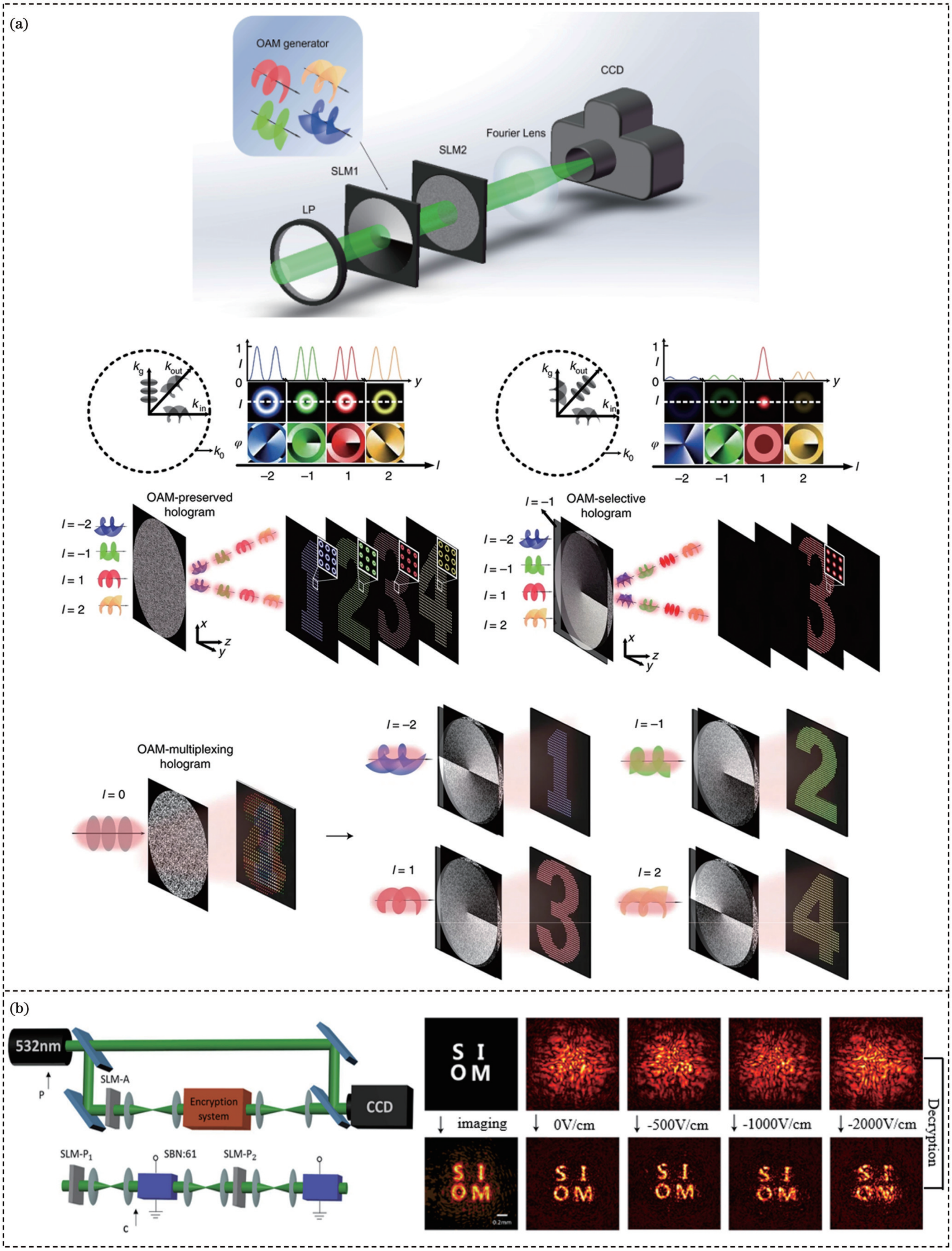

图 9　基于空间光调制器的动态加密系统。(a)基于空间光调制器的轨道角动量全息加密[66]；(b)基于空间光调制器的空间非线性光学图像加密[67]

Fig. 9　Dynamic encryption systems based on spatial light modulator. (a) Holographic encryption of orbital angular momentum based on space light modulator[66]; (b) spatial nonlinear optical image encryption based on spatial light modulator[67]

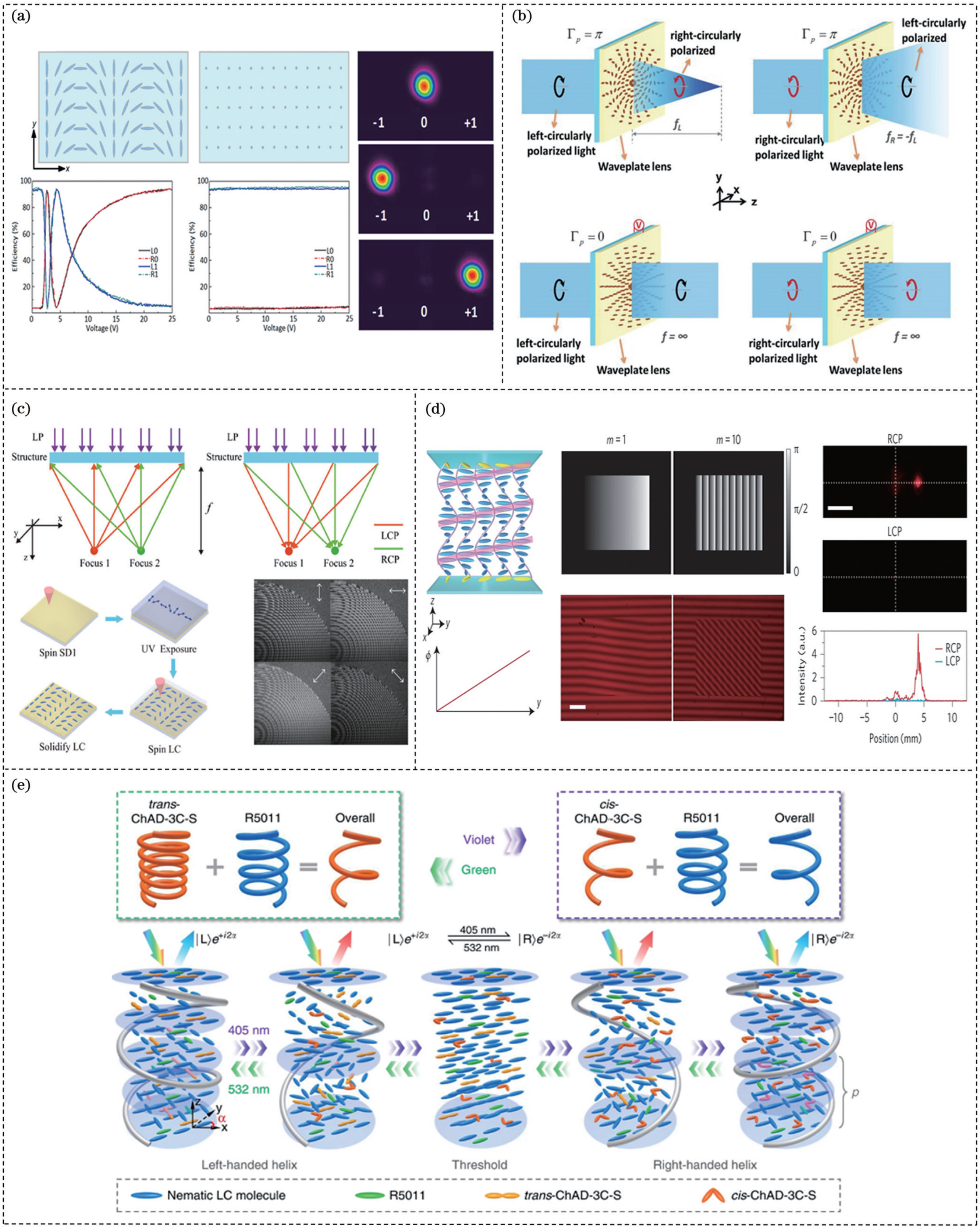

图 10　几何相位型液晶器件。(a)基于几何相位的双频液晶偏振光栅[68]；(b)基于几何相位的偏振切换型液晶透镜[69]；(c)基于几何相位的液晶双焦透镜[70]；(d)不同相位分布下的胆甾相液晶[71]；(e)可光控手性翻转的自组装螺旋超结构[72]

Fig. 10　Geometric phase liquid crystal devices. (a) Dual-frequency liquid crystal polarization grating based on geometric phase[68]; (b) polarization switching liquid crystal lens based on geometric phase[69]; (c) liquid crystal bifocal lens based on geometric phase[70]; (d) cholesteric liquid crystals under different phase distributions[71]; (e) self-assembling spiral superstructure with optically controlled chiral inversion[72]

电场来匹配特定波长的半波条件，从而获得最大衍射效率，越偏离该特定波长，则转化效率越低。为了解决这一问题，2016年，Kobashi等[71]根据螺旋结构的几何相位，将螺旋结构上布拉格反射光的相位控制在0～2π，如图10(d)所示。2019年，Chen等[72]通过混合具有相反手性的光敏分子机器和手性剂，获得了可控手性翻转的自组装螺旋超结构，实现了工作波段连续可调、几何相位共轭的光控可变换光学器件，为动态平面光学器件的实现提供了一种实用方案，如图10(e)所示。

2021年，Li等[73]基于胆甾相液晶固有的自组织螺旋结构，设计了一种染料掺杂手性液晶，对圆偏振发光性能进行调谐，如图11(a)所示。他们设计出具有圆偏振发光性能的可调手性液晶材料，通过调整液晶材料的组分比例和厚度，实现了无串扰的可调圆偏振发

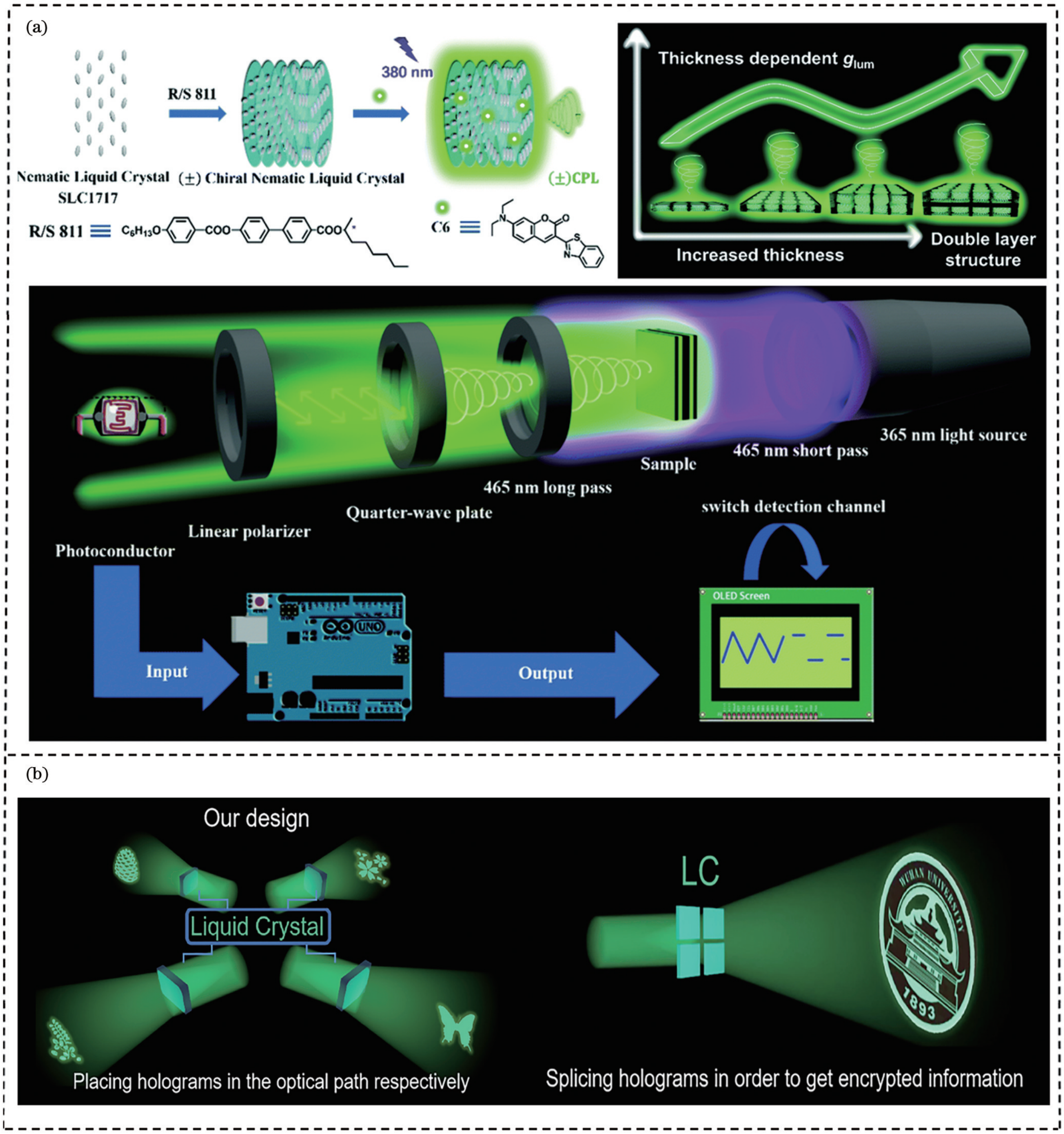

图11　基于液晶的动态加密系统。(a)基于染料掺杂手性液晶对可调圆偏振发光信号进行传输的加密系统示意图[73]；(b)受虎符启发的高安全性液晶全息加密系统示意图[74]

Fig. 11　Dynamic encryption systems based on liquid crystal. (a) Schematic of encryption system for transmission of tunable circularly polarized luminescent signals based on dye-doped chiral liquid crystals[73]; (b) schematic of high security liquid crystal holographic encryption system inspired by Tiger Amulet[74]

光性能。然后他们利用所获得的液晶材料作为输入信号源，建立了一个加密系统以传输圆偏振发光信号。然而，上述加密方案的解码条件不严格，因此加密信息的安全性并不能得到完全保证，在存在波长偏移、偏振状态误差、入射角偏差等情况下，仍然有可能得到隐藏的信息。2023 年，Huang 等[74]设计了一种基于液晶“四合一”全息片的光学加密系统，如图 11(b)所示。该系统受到中国古代虎符思想的启发，只有同一组的四个液晶全息片按照设计好的顺序拼接成一个整体时，才能显示最重要的加密信息，如果全息片被分别放置在光路上或按错误的顺序拼接，则会显示伪装信息。当液晶的面外倾斜角随着外部电压改变时，全息片的全息效率会发生变化，这对解密条件提出了更严苛的要求，从而提高了加密方案的安全性。

2022 年，Chen 等[75]设计了一种融合平板显示和全息投影的超紧凑多功能液晶器件，该器件可以在液晶表面显示灰度图案，同时利用几何相位在远场显示独立的全息图像，如图 12(a)所示。2023 年，Tang 等[76]研究发现，当波长、偏振、观测位置等发生变化时，特定排列的液晶阵列能产生不同的光场响应，通过逆向设计方法可以实现波长、偏振、位置等信息的复用，从而提高器件的功能性和安全性，如图 12(b)所示。他们的设计方案在未增加额外光器件的前提下，将多维度光学信息融合，实现了液晶器件功能的扩展。因此，基于几何相位的液晶器件在偏振转化、宽带、多功能等方面具有优势[77-78]，有望在多通道图像显示、光学加密、宽带液晶透镜等领域中获得应用。

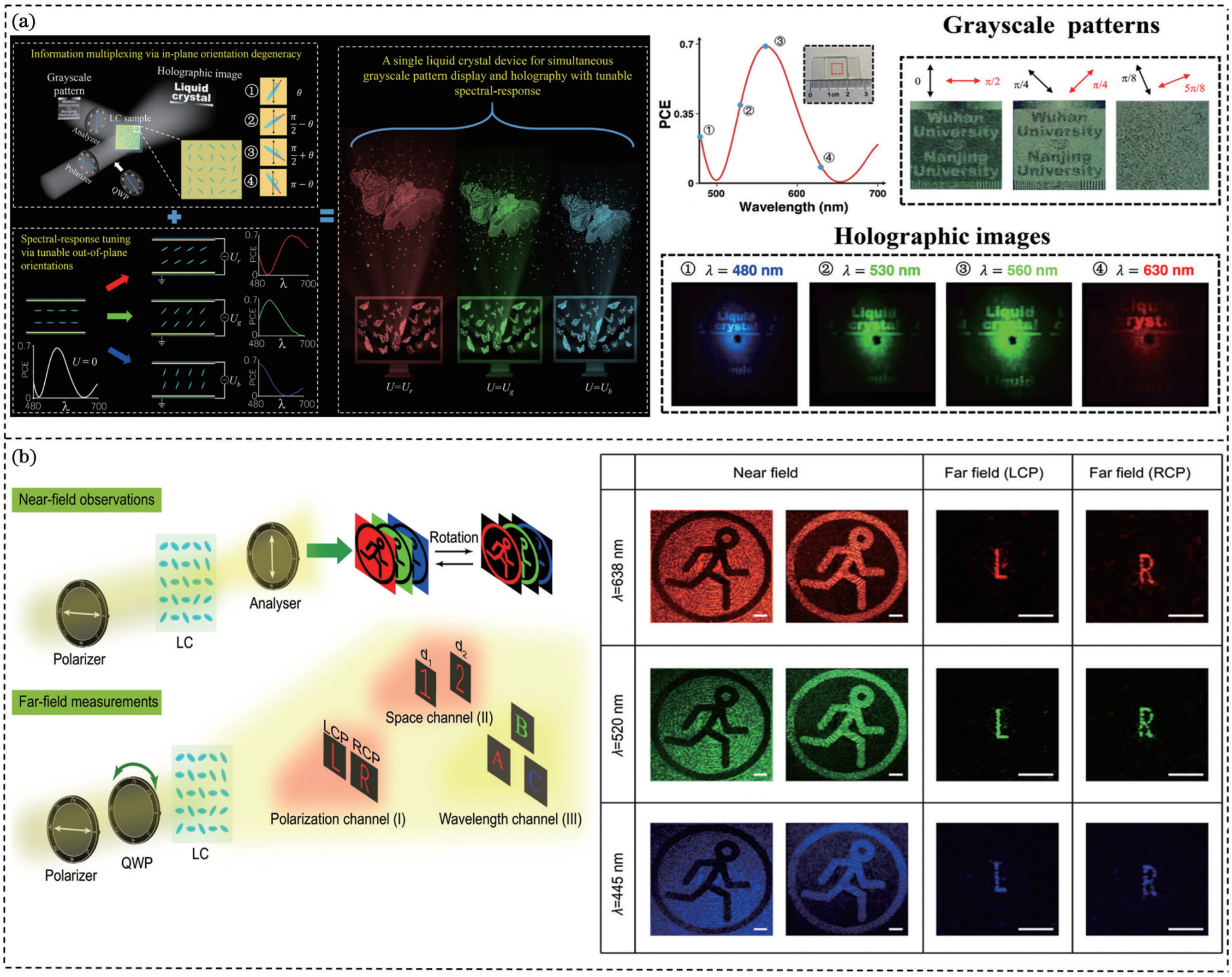

图 12　基于几何相位的多功能液晶器件。(a)近远场图像同时显示的多功能液晶器件[75]；(b)偏振、波长、位置复用的液晶器件[76]

Fig. 12　Multifunctional liquid crystal devices based on geometric phase. (a) Multifunctional liquid crystal device for simultaneous display of near-field and far-field images[75]; (b) liquid crystal device with polarization, wavelength, and position multiplexing[76]

4.3　复振幅型液晶器件

相较于纯振幅或相位调控，复振幅调控可以同时调控光波的振幅和相位，从而增加了调控自由度，在多通道通信、聚焦成像和全息成像等领域中具有较大的应用潜力。根据式(7)，输出光场的正交偏振分量包含 $\sin\theta\cos\theta$，在数学上可以看成两个部分，振幅从 0 连续变化到 1；当取向角 θ 取 0°～90°或 90°～180°时，相位不变，而当取向角 θ 为 90°时，相位突变

π。这意味着除了连续的振幅调控外，还存在 0 和 π 的二元相位调控，如图 13（a）所示[79]。2022 年，Tang 等[79]基于这种调控方式，设计了一种多功能液晶器件，通过改变各向异性液晶分子的方位角，实现了正弦形式的复振幅调控，利用改进后的 GS 算法，在液晶平面和全息成像平面上同时加入预设的强度约束，通过有限次的优化迭代，获得了目标相位分布，从而实现了近远场图像的同时显示，如图 13（b）、（c）所示。为了进一步增加信息容量，他们通过引入位置复用和空间复用方法，实现了三通道和四通道信息的编码、解码。另外，由于归一化的复振幅调控仅依赖于液晶分子的取向角，所设计的液晶器件表现出了宽带特性。

2023 年，Xie 等[80]通过进一步优化近场图像，在两

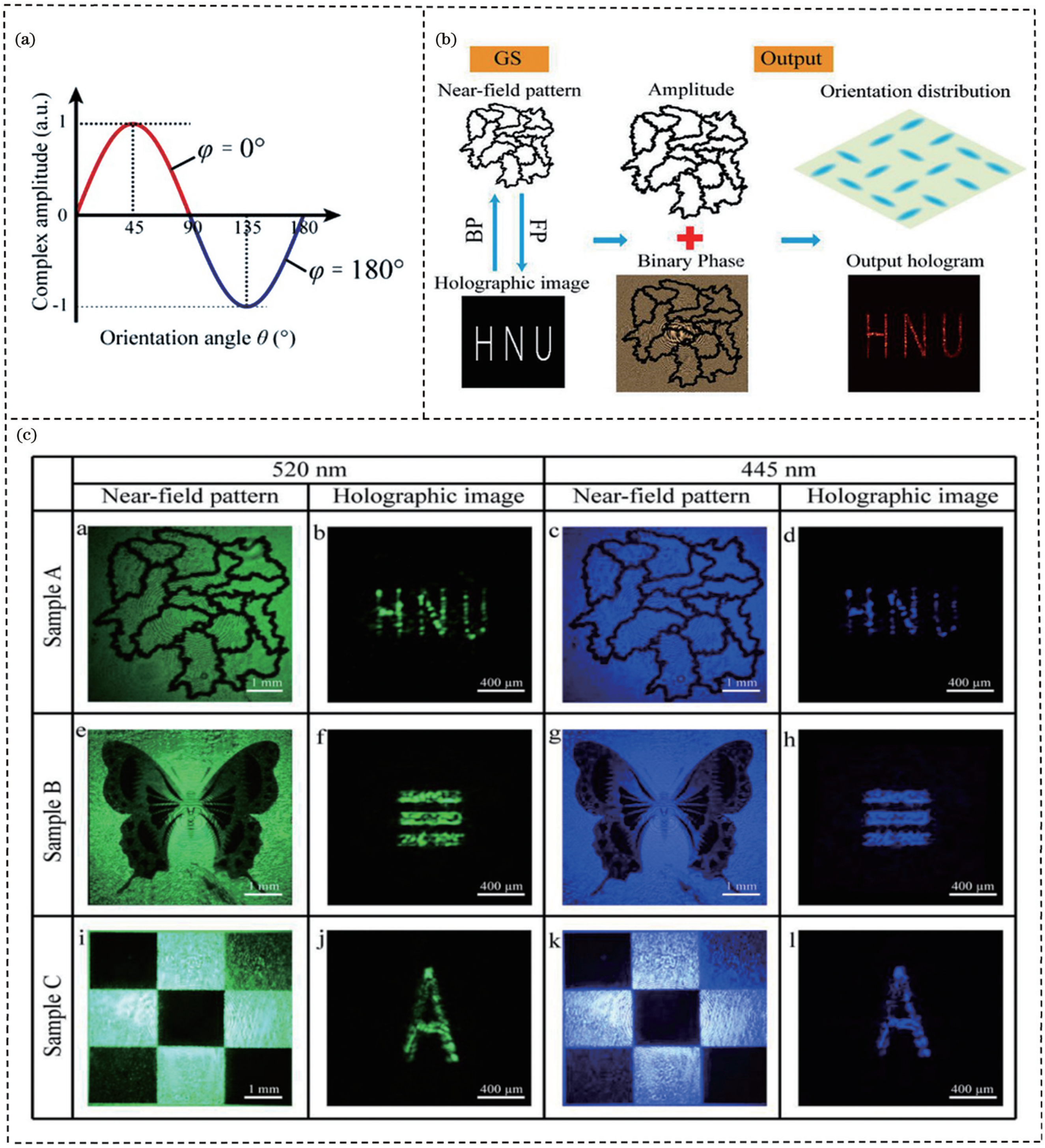

图 13 具有表面显示和远场全息显示功能的多功能液晶器件[79]。（a）液晶分子在正交偏振光路中的复振幅调控特性；（b）器件设计原理示意图；（c）实验测试结果

Fig. 13 Multifunctional liquid crystal device with surface display and far-field holographic display[79]. (a) Complex amplitude modulation of liquid crystal molecules in orthogonal polarized light paths; (b) schematic of device design principle; (c) experimental test results

个独立的近场通道中显示了二进制图像，并且没有出现串扰，同时在远场显示了一个全息图像，实现了三通道显示，如图 14 所示。根据式(7)，他们将液晶器件旋转 22.5°，这时出射光场中的正交分量强度变为

$$I_y = = \left(\frac{t_u - t_v}{2}\right)^2 \sin^2(2\theta - 45^\circ)。\qquad (9)$$

因此将旋转前后每个液晶分子的旋向角和光强进行对应，可获得两个独立的二进制图像；同时，他们通过控制电压来开启或关闭图像，证明了液晶分子的电场可调性。这种技术在多通道图像显示、光学防伪、加密、存储、安全识别、增强现实/虚拟现实(AR/VR)设备等光学领域中具有广阔应用的前景。

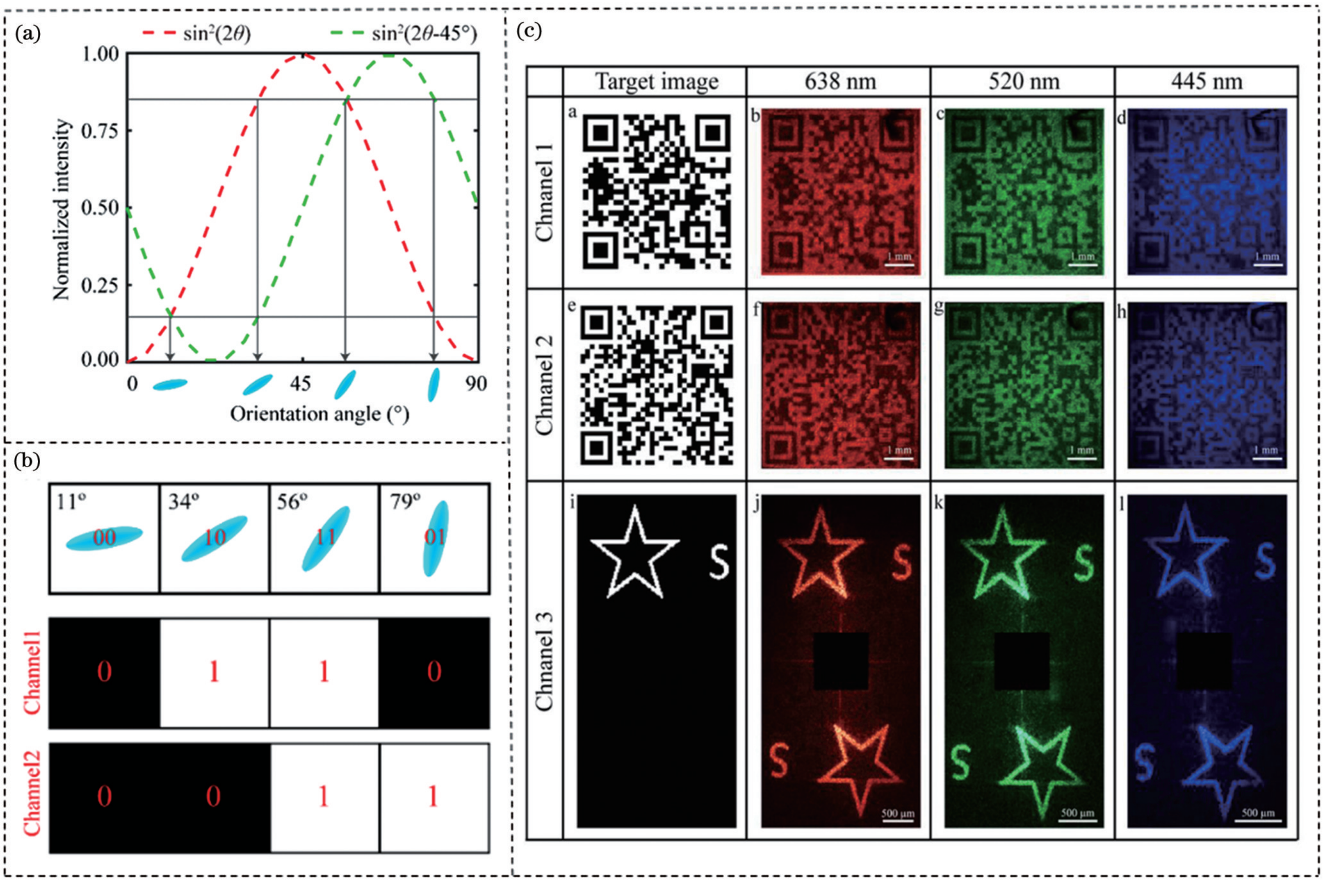

图 14　具有多通道表面图像显示与远场全息显示功能的多功能液晶器件[80]。(a)液晶分子旋转前后的归一化强度与液晶取向角 θ 的关系；(b)液晶分子的四种取向角及其对应的双通道二进制强度编码；(c)实验测试结果

Fig. 14　Multifunctional liquid crystal device with multi-channel surface image display and far-field holographic display[80]. (a) Relationship between normalized strength of liquid crystal molecules and orientation angle θ before and after rotation; (b) four orientation angles of liquid crystal molecules and their corresponding binary intensity codes; (c) experimental test result

4.4　液晶-超表面动态调控器件

超表面可以灵活地调控光波的振幅、相位或偏振等信息[81-82]，得到了国内外学者的广泛关注[83-89]。但是，确定的超表面结构存在难以动态调控的问题。利用电场、磁场或温度等变化可以动态调控液晶，因此，将超表面与液晶结合实现光学特性的动态控制具有非常重要的意义。2021 年，Li 等[90]提出了一种电控的偏振相关加密显示方法，此方法主要利用聚合物分散液晶实现电控开关的效果，为偏振相关的超表面结构色增加了额外的加密自由度，如图 15(a)所示。他们基于液晶和铝纳米孔阵列集成器件获得了高质量加密图像和二维码，这些图像和二维码具有电控切换、偏振相关等特性。2021 年，Zhu 等[91]受电寻址空间光调制器的启发，基于二元全息算法设计了一种与向列相液晶集成的超表面器件，如图 15(b)所示。他们改进了计算机全息图生成算法，获得了与电调制模式相关的三张全息图，并提出了一种基于液晶-超表面复合器件的光学加密方法。该加密方法总共需要四个元素进行解密，可以满足各种加密内容的要求。

2021 年，Hu 等[92]利用超表面的偏振操纵能力，设计了一种在可见光范围内与液晶集成的电可调谐多功能偏振相关超表面，如图 16(a)所示。他们将偏振相关的超表面和双折射液晶结合，实现了连续强度调谐和两个偏振通道的切换，展示了可电调谐的单色和多色可切换的全息图和动态变焦。2022 年，Wang 等[93]利用液晶和金超表面复合器件实现了多种光学功能，如图 16(b)所示。他们将金的各向异性超表面作为模

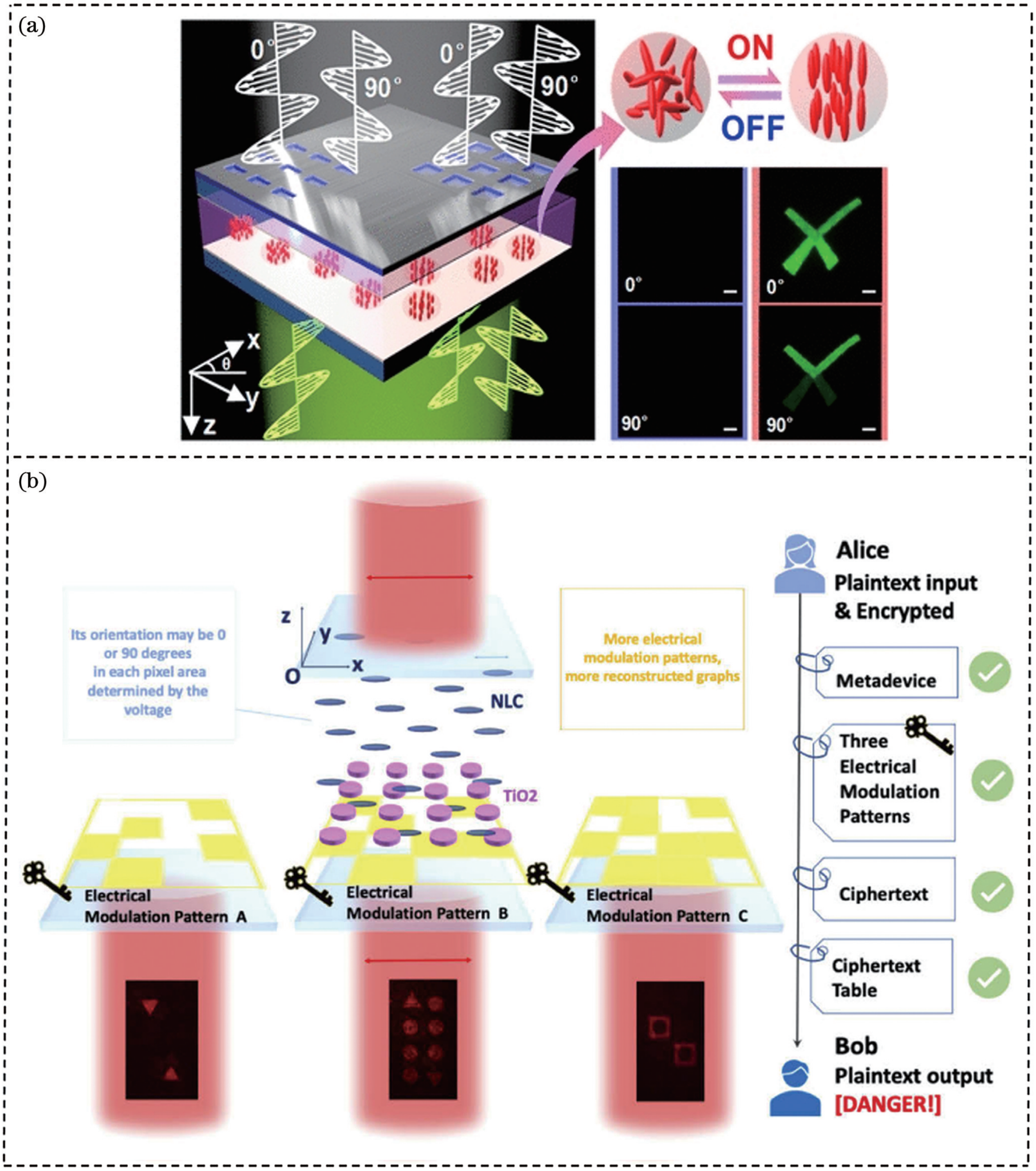

图 15 集成液晶与超表面的调控器件。(a)集成聚合物分散液晶和超表面的光学加密系统示意图[90];(b)集成向列相液晶和超表面的器件示意图[91]

Fig. 15 Modulator components with integrated liquid crystal and metasurface. (a) Schematic of optical encryption system with integrated polymer dispersed liquid crystal and metasurface[90]; (b) schematic of device with integrated nematic liquid crystal and metasurface[91]

板,在超高分辨率(2 μm)区域内对液晶分子进行取向。同时,利用取向的液晶分子动态控制入射光的偏振,进一步实现了金超表面局域等离激元共振的主动调控。因此,液晶-超表面动态调控复合器件在光学加密、图像显示、光通信、防伪和数据存储等领域中都有着广阔的应用前景。

4.5 液晶微型激光器

由于液晶的液态、自组装、可调谐等特性,基于液晶的微型激光器吸引了研究人员的关注[94-96]。2022 年,Muszyński 等[97]将染料分子分散在液晶微腔中,开

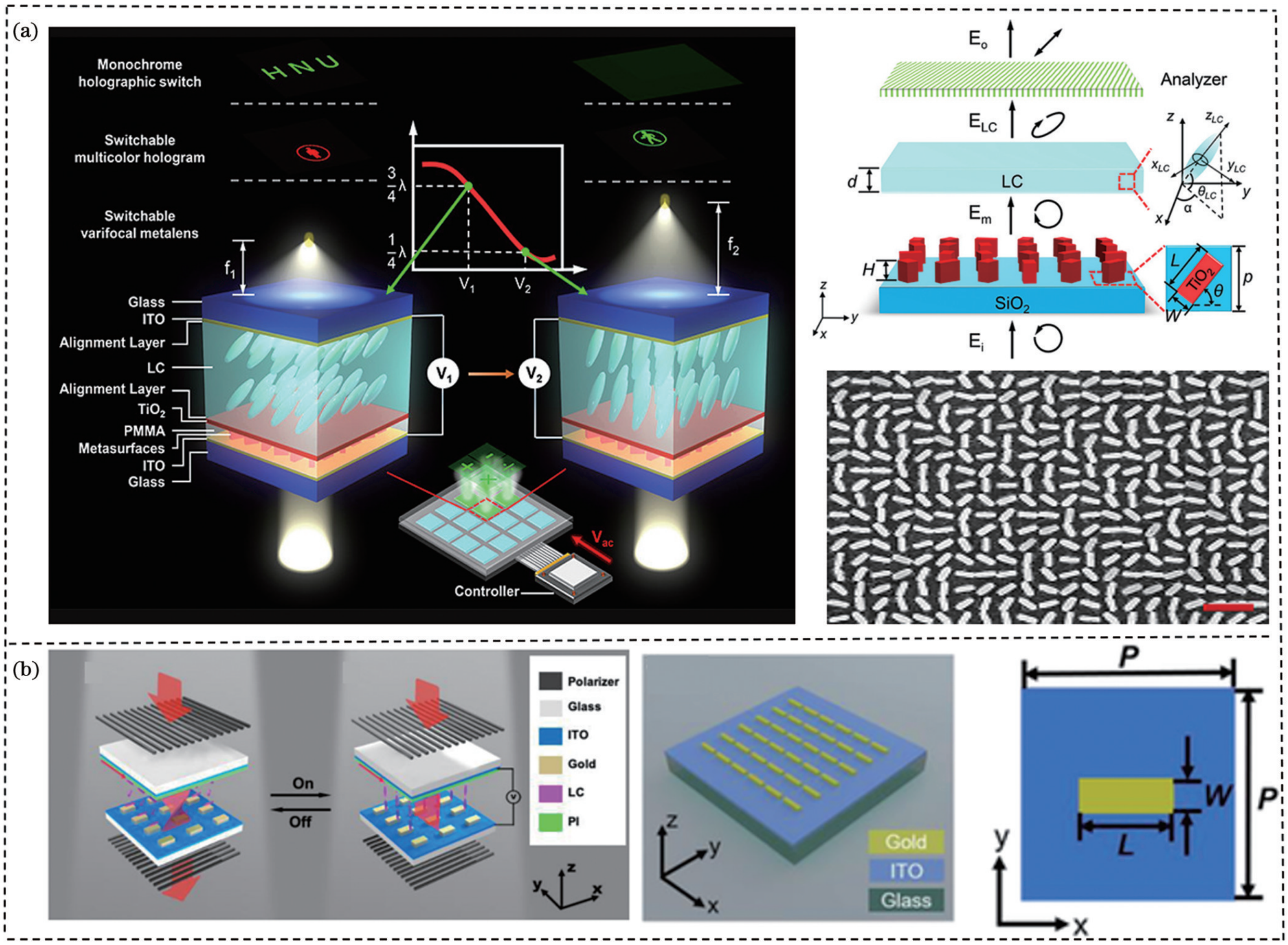

图 16　液晶-超表面动态调控器件。(a)集成液晶的电可调谐多功能偏振依赖超表面示意图[92]；(b)电可调谐液晶负载超表面示意图[93]

Fig. 16　Liquid crystal-metasurface dynamic control devices. (a) Schematic of electrically tunable multifunctional polarimetric dependent metasurface with integrated liquid crystal[92]; (b) schematic of electrically tunable liquid crystal loaded metasurface[93]

发了一种 540～580 nm 范围内可调谐的微型激光器件，且该激光器微腔表面上存在自旋螺旋，激光器可发射两束具有不同偏振角度的圆偏振光，如图 17(a)所示。为了解决激光器工作温域较窄的问题，2022 年，Chen 等[98]通过调控蓝相液晶的可聚合液晶单体含量，获得了稳定的蓝相聚合物支架，将染料分子掺入后，获得了工作温域为 25～230 ℃的蓝相液晶激光器件，如图 17(b)所示。这类基于液晶的微型激光器件在未来激光显示、量子通信、生物诊断等领域中具有重要的应用前景。

4.6　液晶的其他光场调控应用

液晶的光场除了具有振幅、相位、动态可调谐等特性外，在非线性光学[99-101]、光学角动量调控[102-107]等方面也具有优势。近年来，铁电向列相液晶材料的发展为开发液晶的非线性光学特性提供了可能性，其除了具备传统向列相的特征外，还具备超高的介电常数、出色的非线性光学特性及对电场的高响应灵敏度[108-111]。2022 年，Folcia 等[112]基于铁电向列相液晶材料进行了光学二次谐波产生的研究，发现该材料在透明状态下的非线性磁化率为 5.6 pm/V，如图 18(a)所示，验证了铁电向列相液晶在非线性光学领域中的应用。2022 年，Zhao 等[113]使用具有极化螺旋的铁电向列相液晶开发了一种新型非线性光学系统，该系统扩展了传统周期性极化晶体中的相位匹配方法，如图 18(b)所示。尽管基于铁电向列相液晶的非线性方案存在一些缺点，如在室温下无法适用、二次谐波转换效率低等，但铁电向列相液晶的非线性光学特性仍然值得研究，在频率转换、光开关设计等领域中具有潜在的应用前景。

2022 年，Liu 等[114]设计了一种基于几何相位的新型液晶平面光学器件。他们将二值精细结构与渐变几何相位结构集成到一个器件中，获得了偏振可控、模式分布可定制的轨道角动量光束三维阵列，如图 19(a)所示。2022 年，Hu 等[115]设计了一种可逆的光控开关，并构造了一个具有稳定输出的液晶激光体系。他们通过调控光子微腔内的谐振与微腔外的传输之间的耦合平衡，实现了包含自旋角动量、轨道角动量的四维度可调控激光编码技术，如图 19(b)所示。

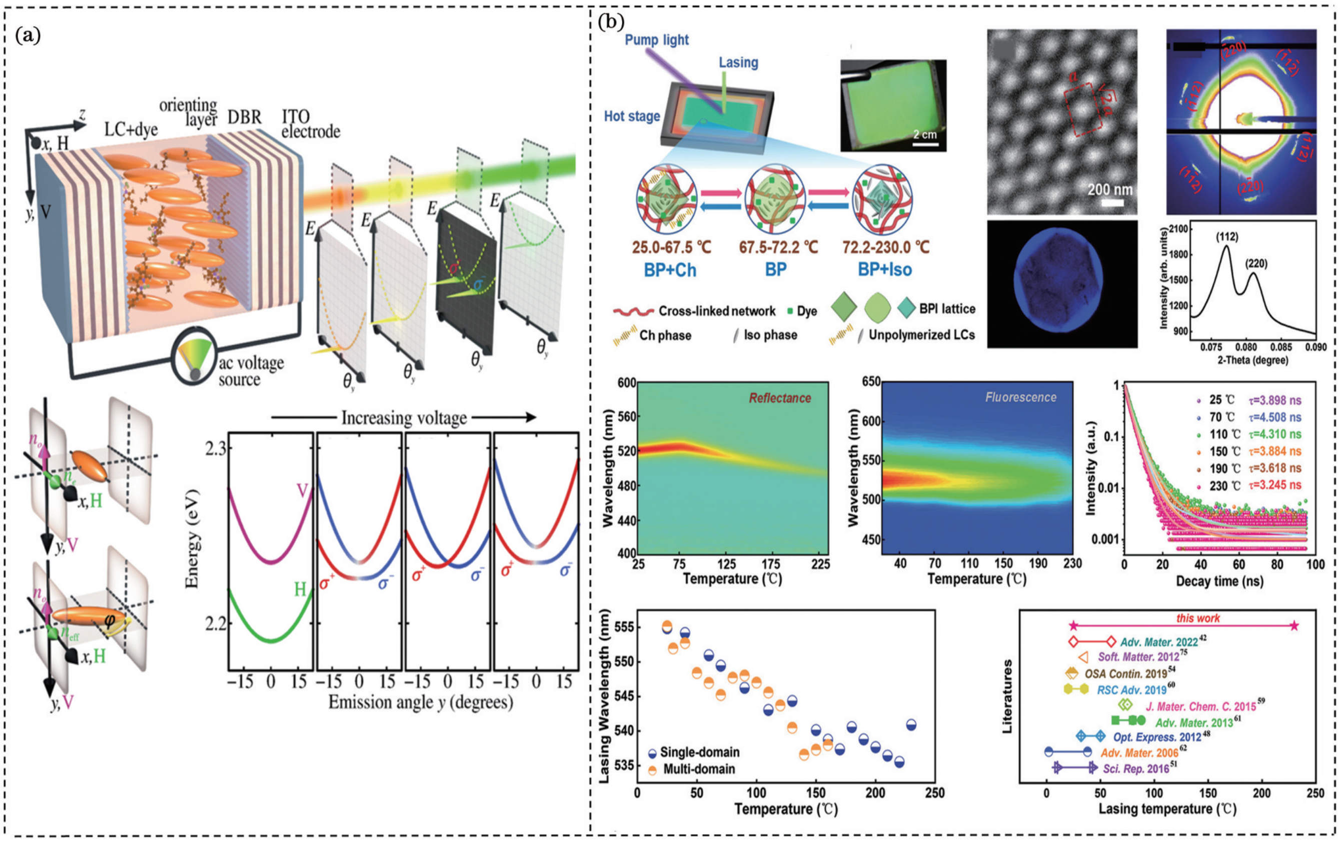

图 17　可调谐液晶微型激光器件。(a)宽波段、双光出射液晶激光器件[97]；(b)宽温域蓝相液晶激光器件[98]

Fig. 17　Tunable liquid crystal micro laser devices. (a) Wide-band and dual outgoing liquid crystal laser[97]; (b) blue phase liquid crystal laser with wide temperature domain[98]

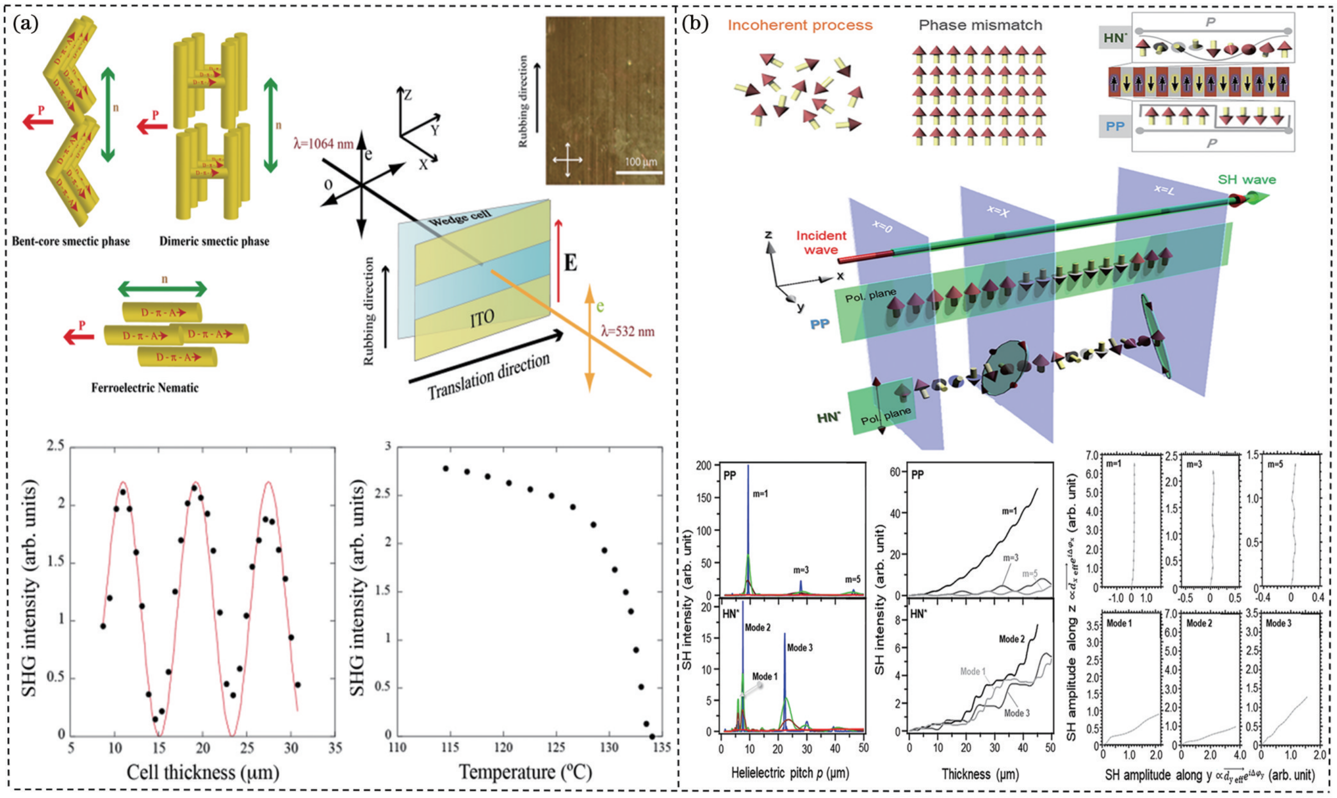

图 18　基于液晶的非线性光场调控。(a)铁电向列相液晶的非线性特性研究[112]；(b)基于螺旋铁电向列相液晶的非线性特性系统[113]

Fig. 18　Nonlinear light field control based on liquid crystal. (a) Study on nonlinear properties of ferroelectric nematic liquid crystals[112]; (b) nonlinear property system based on spiral ferroelectric nematic liquid crystals[113]

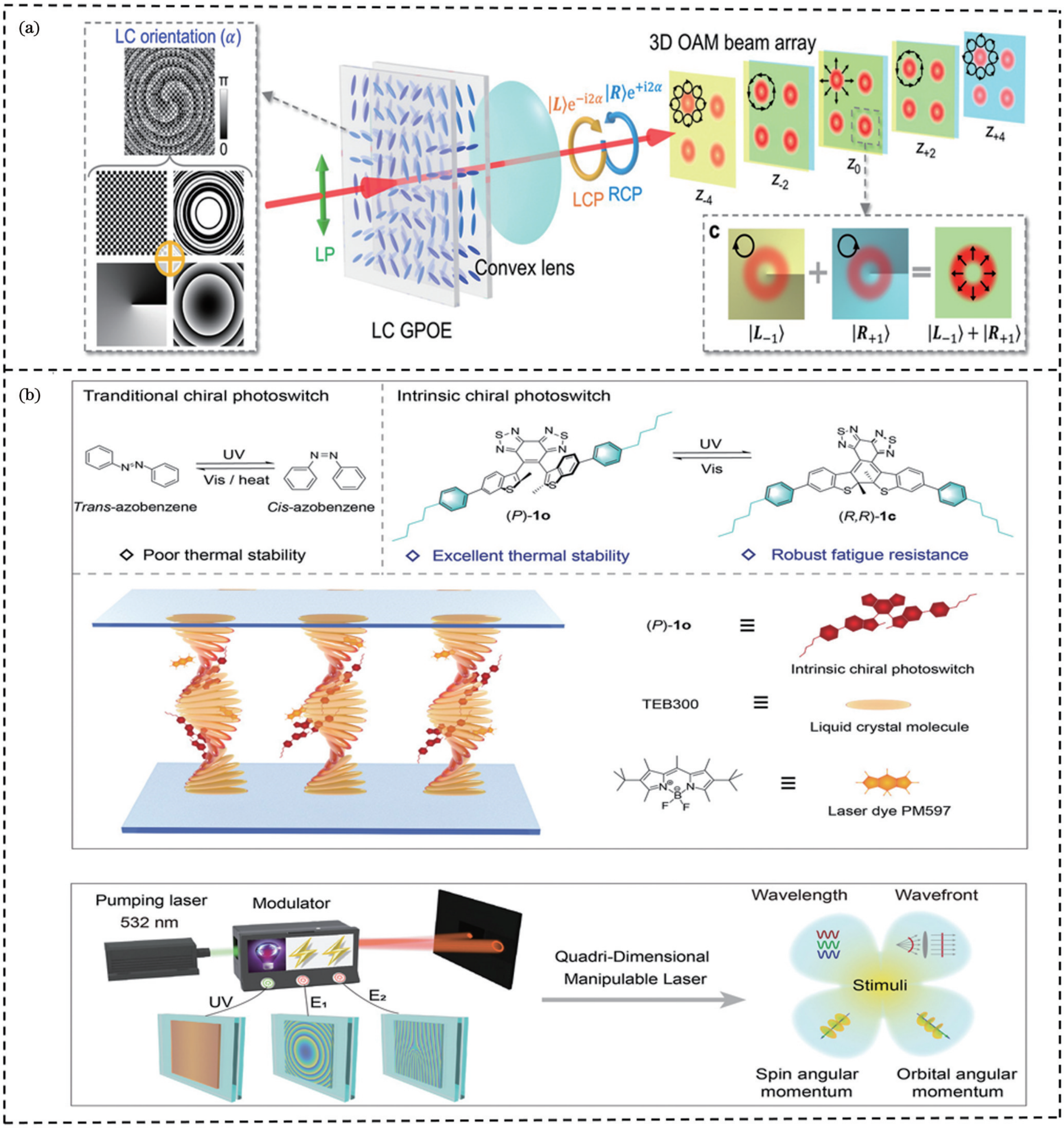

图 19　基于液晶器件的光场角动量调控。(a)基于液晶几何相位的轨道角动量光束三维阵列[114]；(b)四维度光场可调谐液晶器件[115]

Fig. 19　Control of angular momentum of light field based on liquid crystal devices. (a) Three-dimensional array of orbital angular momentum beams based on geometric phase of liquid crystal[114]; (b) four-dimensional optical tunable liquid crystal device[115]

5　总结与展望

随着液晶理论研究的深入和液晶加工技术的进展，基于液晶的光场调控技术向着多样化、多功能、多维度方向发展，从传统显示中的振幅调控发展到几何相位调控和复振幅调控，从静态调控发展到动态调控，从单功能发展到多功能集成。结合液晶相关技术工艺成熟、成本低、大尺寸等特点，详细介绍了基于液晶的多维度光场调控的研究进展。近年来多功能液晶器件的设计和加工解决了液晶器件功能单一的问题，同时液晶作为一种相对有序的材料，在动态调控方面具有得天独厚的优势，结合液晶动态调控性能的超表面作为复合结构，可以实现更多功能的集成。目前，基于液晶的多维度光场调控技术仍然存在一些尚未解决的问题。这些问题包括如何实现多功能多层集成化液晶器件、宽带消色差液晶器件、偏振无关型液晶器件、液晶器件纵向色差校正、变焦液晶透镜、新型液晶(例如胆甾相液晶)与超表面结合等，同时，在液晶加工过程中，

当像素尺寸缩小时需要保证加工精度。因此，需要广大研究人员聚焦上述领域，深入开展相关研究工作。我们相信，基于液晶的光学器件将在光学加密、图像显示、光通信和数据存储等领域中发挥越来越重要的作用。

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Advances in Multi-Dimensional Light Field Modulation Based on Liquid Crystal

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Abstract

Significance As a class of soft functional materials that exhibit both liquid and solid-like properties, liquid crystals can simultaneously show fluidity and crystal anisotropy, and have been widely applied in the fields of image display, integrated optoelectronics, optical communication, and others. In the past decades, with the development of the liquid crystal theory and processing technology, the research on liquid crystals has gradually matured from the conventional display to advanced liquid crystal photonics, which is of great significance for the realization of integrated, intelligent, and miniaturized optical systems. Liquid crystals can exhibit abundant phase states, including smectic, nematic, cholesteric, and blue phases. Each phase state has its unique properties and can be applied in different fields, including tunable optical devices and polarization converters. Therefore, the light modulation characteristics of liquid crystals, including their amplitude, phase, and polarization, are investigated. Based on these properties, a variety of liquid crystal devices can be designed to replace the conventional refraction optical elements, such as gratings, focusing lenses, spiral phase plates, beam steering devices, and holographic imaging devices. For the successful fabrication of devices, liquid crystal molecules should be controlled precisely in terms of the friction orientation, tilt evaporation orientation, and photoalignment. Each technology has its unique advantages from the perspective of different applications. In addition, liquid crystals can be dynamically controlled by varying the electric field, magnetic field, or temperature. The use of liquid crystals in the field of lasers and metasurfaces is of great significance to prepare tunable liquid crystal micro-laser and liquid crystal metasurface composite devices. Therefore, it is extremely important and necessary to summarize the liquid crystal modulation techniques to guide the future development of this field.

Progress This paper summarizes the research progress in multi-dimensional light modulation enabled by liquid crystals. The light modulation characteristics of liquid crystals are derived from their birefringence properties through the Jones matrix (Fig. 2). A variety of photoalignment technologies, including mask exposure, interference exposure, direct write exposure, plasma mask exposure, and dynamic mask exposure, are presented (Fig. 3). According to the light modulation characteristics of liquid crystals, liquid crystal devices are classified into amplitude, phase, and complex amplitude types. Amplitude-type liquid crystal devices include liquid crystal displays, amplitude-type spatial light modulators, and liquid crystal smart windows (Figs. 5–7). Phase-type liquid crystal devices include phase-type spatial light modulators and geometric phase-type liquid crystal devices. The researchers developed an orbital angular momentum holographic encryption system based on a phase-type spatial light modulator. For geometric-phase liquid crystal devices, some geometric-phase nematic liquid crystal devices are first introduced. In order to overcome the low polarization conversion efficiency of nematic liquid crystals, the researchers from Nanjing University obtained a chiral flip controllable self-assembled spiral superstructure by mixing a photosensitive molecular machine with a chiral agent with opposite chirality. An optically controlled transformable optical device with a continuously adjustable working band and geometrically conjugate phase was realized (Fig. 10). By introducing the extension of Marius′ law to the orientation arrangement of liquid crystal molecules, the researchers from Wuhan University realized the independent regulation of the amplitude and phase of light waves, realizing a breakthrough in ultra-compact multifunctional liquid crystal devices (Fig. 12). Based on the Jones matrix, the researchers from Hunan University found that binary phase modulation also contributes to continuous amplitude modulation and realized a complex amplitude liquid crystal device (Figs. 13 and 14). The concept of metasurface has attracted considerable attention in recent years. However, once the structure of the metasurface is determined, it is difficult to realize dynamic modulation. To overcome this situation, researchers have combined metasurfaces with liquid crystals to achieve dynamic control of the optical properties of the integrated system (Figs. 15 and 16). Benefiting from the liquid , self-assembling, and tunable properties of liquid crystals, researchers have developed liquid crystal-based micro-lasers (Fig. 17). In addition, other light modulation applications enabled by liquid crystals, including nonlinear optical effects and optical angular momentum modulation, have been discovered (Figs. 18 and 19).

Conclusions and Prospects With the development of the liquid crystal research theory and fabrication/processing technologies, different light-modulation technologies based on liquid crystals have been developed for various optical applications ranging from conventional display amplitude modulation to geometric phase modulation, and complex amplitude modulation, static to dynamic modulation, and single-function to multi-function integration. This paper outlines the recent research progress of multi-dimensional light modulation based on liquid crystals, especially the design and processing of multifunctional liquid crystal devices. At the same time, combining a dynamically controllable liquid crystal with a metasurface to form a composite structure can integrate more functions in a single device. The field of liquid crystals also faces certain issues in aspects ranging from structural design to device fabrication, such as how to achieve multifunctional multilayer integrated liquid crystal devices, broadband achromatic liquid crystal devices, polarization-independent liquid crystal devices, vertical chromatic aberration correction of liquid crystal devices, and zoom liquid crystal lenses. Therefore, it is necessary to focus on the above areas, and we believe that optical devices based on liquid crystals will play an increasingly important role in optical encryption, image display, optical communication, and data storage.

Key words optical data storage; liquid crystal; light field modulation; anisotropy; geometric phase; multifunction; optical encryption