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张艺瑜, 宋春风, 郭金宝

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基于聚合物稳定液晶的智能调光膜研究进展

张艺瑜, 宋春风, 郭金宝*

(北京化工大学 材料科学与工程学院, 北京 100029)

摘要: 聚合物稳定液晶(Polymer Stabilized Liquid Crystals, PSLCs)是一种含少量聚合物网络的液晶-聚合物复合材料,凭借良好的光学性能及外场响应性,PSLCs 可被用作电子纸、调光膜、传感器等器件。近年来,随着能源供应的紧张以及保护环境的实际需求,调光膜的重要性逐渐被凸显。PSLCs 调光膜作为其中的一个重要分支,根据响应方式的不同其又可分为多种类型。为了进一步改善 PSLCs 调光膜的光学性能,丰富其外场调控性,研究者从纳米粒子掺杂、染料掺杂以及聚合物网络结构改进等方面入手开展了许多研究。本文主要对近些年基于聚合物稳定液晶材料的智能调光膜领域研究进展进行了系统总结,并对未来 PSLCs 调光膜的发展趋势做出了展望。

关键词: 聚合物稳定液晶;智能调光膜;外场调控;节能

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Research progress of smart windows based on polymer stabilized liquid crystals

ZHANG Yi-yu, SONG Chun-feng, GUO Jin-bao*

(College of Materials Science and Engineering, Beijing University of Chemical Technology, Beijing 100029, China)

Abstract: Polymer stabilized liquid crystals (PSLCs) are a class of liquid crystal/polymer composite materials containing a small amount of polymer network. Due to their good optical properties and field responsive characteristics, they can be used as electronic paper, smart windows, sensors and other devices. In recent years, with the pressure of energy supply and the actual need of environment protecting, the importance of smart windows has gradually been highlighted. As the important of the branches, there is a variety of classification of PSLCs-based smart windows depending on the different response mode. In order to further improve their optical properties and enrich its field regulation styles, many researches have been carried out recently from the aspects of nano-particle doping, dye doping and polymer network structure improvement, etc. In this paper, the research progress of PSLCs-based smart windows in the past few years is reviewed and discussed, and the future development trend of PSLCs-based smart windows is forecasted.

Key words: polymer stabilized liquid crystals; smart windows; external-field switching; energy saving

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* 通信联系人, E-mail: guojb@mail.buct.edu.cn

1 引言

有研究表明,在现代社会中,大部分地区将近一半的建筑能耗被用于采暖、冷却和换气等用途^[1],而预计到 22 世纪时,用于制冷的能耗将比现在增加 40 倍左右,这不仅增加了能量的浪费,也同样加剧了因能量生产而带来的环境破坏问题^[2]。近年来,智能材料飞速发展,随着实际需求的增长以及人们环保意识的增强,作为智能材料重要分支的调光膜领域引起了研究人员的广泛关注^[3-4]。调光膜即为一类可对紫外光、可见光、近红外光等多种光波进行动态调控的智能材料^[5-6]。调光膜的种类多样,其中聚合物稳定液晶调光膜以其良好的稳定性以及优异的光学性能占据了重要地位^[7-9]。

液晶因其独特的物化性质一直受到研究人员的密切关注,但单组分的液晶材料有时无法满足生产生活中的实际需求^[10-12]。因此,将聚合物网络与液晶相结合从而得到性能优良的液晶-聚合物复合材料正在成为当今液晶领域研究的一个热点问题^[13-15]。根据复合体系中聚合物网络的含量多少可将其分成两类,即聚合物含量较高的聚合物分散液晶(Polymer Dispersed Liquid Crystals, PDLCs)和聚合物含量较低(常低于 10%)的聚合物稳定液晶(Polymer Stabilized Liquid Crystals, PSLCs)^[16-17]。在聚合物分散液晶中,聚合物含量较高,形成的聚合物网络比较密集,因此有较好的力学性能^[18]。其中,液晶以微滴形式存在于聚合物网络的空隙中,由于液晶随机取向,使得 PDLCs 膜在初始时呈散射态,当施加一定强度的外加电场后,液晶有序化,使得液晶膜变透明^[19-22]。而聚合物稳定液晶由于所含的聚合物网络较少,因此液晶膜对于外场刺激具有很快的响应速度以及极好的初始态透明度而无需像 PDLCs 那般消耗电能^[23]。此外,PSLCs 薄膜较低的雾度和较宽的视角使其在显示、光开关、相调节器等方面具有相当的应用潜力^[24-28]。

PSLCs 调光膜根据响应方式的不同主要分为电调控、温度调控以及光调控等几类^[29-30]。其中,电调控智能窗的液晶组分可选为向列相液晶^[31]、胆甾相液晶^[32]或近晶相液晶^[33],3 种液晶

体系的调光膜在一定条件下均可实现对透光率的调控。在聚合物稳定向列液晶调光膜中,液晶分子经取向后竖直排列,调光膜呈透明态;当向液晶膜施加电场后,负性液晶分子长轴倾向于平行基板排列,因而调光膜对入射光产生比较强烈的散射作用^[34]。而在聚合物稳定胆甾相液晶智能调光膜中,则多半需要使液晶在初始态平面取向,而后通过不同频率、不同大小的电场来调控胆甾相液晶至不同织构以改变液晶膜的光学性能。不少研究也会利用胆甾液晶的波段反射特性,通过控制胆甾相液晶的螺距大小,改变液晶体系的反射波段,从而实现对可见光区及近红外光区入射光的精准调控^[35-37]。在近来的研究中,调光膜的温度调控或光调控主要是通过液晶在升温时发生的相态变化以及掺杂一些可异构化的温度响应或光响应手性分子等途径来实现,利用液晶在相转变前后光学性质的改变以及温度响应或光响应分子在不同结构时的手性差异,达成调节液晶分子排布的目的,从而实现液晶膜光学性能的改变^[38]。

本文着重分析了各种外场响应型的 PSLCs 智能调光膜的制备方法、工作原理及相关性能,总结了近些年来国内外研究人员在该领域取得的研究进展。最后,对基于 PSLCs 的智能调光膜未来的发展趋势做了一定的展望。

2 PSLCs 调光膜

2.1 电场响应调光膜

液晶分子的介电各向异性使得自身的空间排列会因外界电场的有无做出改变,并进而影响液晶器件的宏观透光率。由于电场调控响应速度快,调控效果稳定,因此是当下非常普遍的一种 PSLCs 调光膜调控方式^[39-40]。

液晶调光膜的性能与液晶的取向程度息息相关,良好的液晶取向对于液晶调光膜的光学性能有很大的提升。其中聚酰亚胺取向层因其取向性能以及稳定性良好而受到了许多研究人员的青睐^[41-46]。但由于 PI 取向层往往由前驱体聚酰胺酸 PAA 经近 200 °C 高温固化而得,使得绝大多数的柔性基板因难以承受如此高温而无法应用。因此,Zhang^[47]等进行了详细研究来探讨低温固化对 PI 取向效果的影响。通过对一系列在不同

固化温度下得到的 PI 取向层进行性能对比,确定了前驱体聚酰胺酸 PAA 溶液固化的温度范围,并以低温固化 PI 作取向层的 PET 柔性材料作基板,得到了电光性能良好的 PS LCs 调光膜。文璞山^[48]等合成了 3 种热稳定性较高的可溶性聚酰亚胺,经摩擦后的薄膜具有较好的取向性能,有望应用于柔性光学薄膜。Hu^[49]等以 PI 为取向层,实现了反式 PS LCs 器件的制备,如图 1 所示。该项研究主要着眼于聚合物网络的含量及厚度对液晶调光膜的光学性能的影响,成功制得一种关态雾度低至 3.5%、开态雾度高达 98% 的光学性能优良的液晶膜。此外,该方法所制得的液晶膜电光性能及热稳定性均较优异,均匀性亦佳,可制得 40 cm×50 cm 大小的智能窗,有望成为新一代智能窗的蓝本。

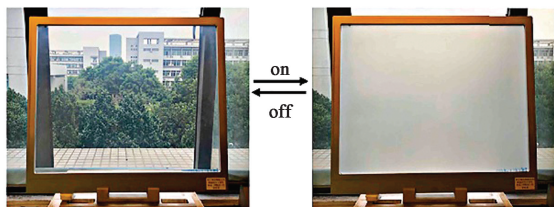


图 1 (40 cm×50 cm) 智能窗在关(0 V)和开(40 V)状态的实物图^[49]

Fig.1 Prototype of a (40 cm×50 cm) smart window in the off state (0 V) and on state (40 V)

Meng^[50]等则进一步改善了取向层的制作工艺,将液晶性聚合物网络引入到取向层中,通过热致相分离的方法得到了一种厚度分布不均匀的取向层,如图 2(a)所示。研究认为,因热致相分离导致的基板表面不平整的取向层结构不会影响聚酰亚胺垂直取向层的取向作用,故而不会降低液晶膜的初始透明态,且由于基板表面形成的许多不平整的凸起会使得 PS LCs 膜的内部在加电后会形成更多倾角不同的散射微畴,因此所形成的液晶膜的散射态有明显提升。此外,研究还针对液晶膜厚度对光电性能的影响进行了探究,得到了该体系液晶膜综合性能最佳时的参数。所得液晶膜有望应用于智能窗及透明显示器件等领域中。

由于染料的吸收各向异性可以与液晶分子的取向状态产生一定的配合,且某些染料对于 PS LCs 智能窗的电光性能有较明显提升,因此,

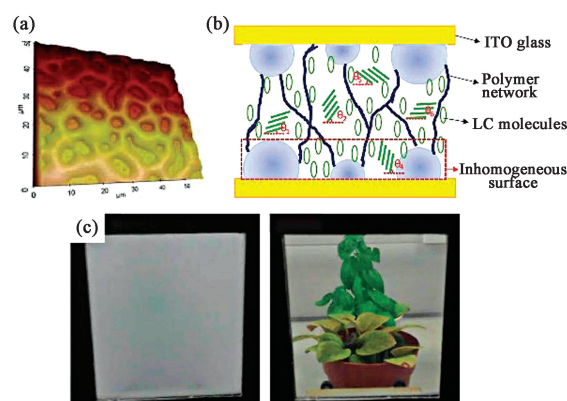


图 2 (a)热处理后所得取向层的形态;(b)加电时,不均匀取向液晶膜内的随机预倾角微畴示意图;(c)100 cm² PS LCs 的开关态实物照片(背景植物距离膜 20 cm)^[50]。

Fig.2 (a) Alignment surface morphologies with inhomogeneity treatment; (b) Random pretilt domains schematic at power-on state based on inhomogeneous alignment surface; (c) On and off- state of a 100 cm² PS LCs smart window (the background plant was held at a distance of 20 cm).

由二向色性染料和液晶形成的宾主体系近来也逐渐成为研究热点^[51-53]。所谓二向色性染料,是指沿染料分子长轴指向和短轴指向对偏振方向与之平行的偏振光具有差异性吸收的染料,因此也可被称为吸收二向色性染料^[54-55]。自 20 世纪 60 年代 Heilmeyer 与 Zanoni 报道了第一例液晶与二向色性染料混合构筑形成的宾主体系以来,该类体系便被人们广泛进行了制备与研究^[56-57]。由于单一的 PS LCs 体系调光膜的雾度相对较低,一般只有 40%~50%,难以满足生产生活中的实际需求,严重限制了 PS LCs 调光膜的应用。因此 Sun^[58]等提出了一种利用有机染料提高调光膜对比度的方法,如图 3 所示。研究发现,非二向色性染料更易着色,使得 PS LCs 膜的开、关两态的颜色浓重,从而不利于提高 PS LCs 的开关态对比度;二向色性染料而由于自身的吸光各向异性使得样品在关断状态只显示出轻微的颜色,在开启状态显示出较为浓重的颜色,从而在一定程度上增强了开关两种状态下的对比度。因此,他们制备了两种染料混合的 PS LCs 调光膜。研究结果表明,由于减色效应,PS LCs 调光膜在关断状态时近乎无色,而加电后则显示出浓厚的颜色,大幅

增加了液晶膜的开关对比度,同时也为从美学角度出发,通过掺入混合染料制作彩色 PSLCs 智能窗提供了一种可行的方法。

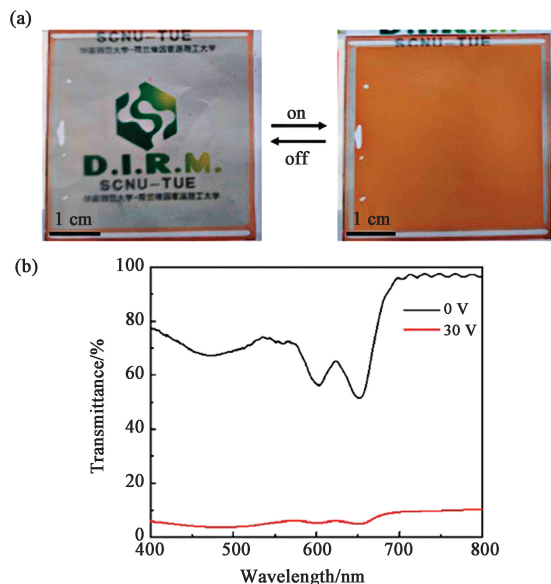


图 3 (a)PSLCs 膜掺杂混合染料的实物图;(b)掺杂混合染料的 PSLCs 的透光率^[58]。

Fig.3 (a) Photograph of PSLCs doped with mixed dyes; (b) Transmittance of PSLCs doped with mixed dyes.

某些纳米颗粒可以改善液晶的介电各向异性以及分子排列,并且还可吸附体系中可能存在的杂质离子,进而优化 PSLC 的电光性能,因此向体系中添加各类的纳米粒子也是提升 PSLCs 智能窗性能的一种常用方法^[59-64]。Park^[65]等通过向 PSLCs 体系中添加 TiSiO_4 、 BaTiO_3 、 SrTiO_3 以及 BaTiO_3 - SrTiO_3 混合粒子等不同种类的无机纳米粒子,改善了调光膜的电光性能,如图 4(a)所示。研究发现当纳米粒子的含量为 0.1%(质量分数)左右时,能够在不影响液晶膜光学性能的前提下提高其电性能。Yan^[66-67]等向 PSLCs 体系中加入银纳米线以及银纳米粒子,通过对照实验,得出了 PSLCs 驱动电压下降幅度最大时的银纳米线的掺杂含量,同样证明了银纳米线可以有效改善 PSLCs 调光膜的电光性能,如图 4(b)所示。

对聚合物网络结构的改进优化是另外一种提高液晶膜电光性能的方法。为了降低传统 PSLCs 的长期稳定性不足以及解决传统柔性调光膜难以经受大角度弯折的问题^[68-69],Yoon^[70]

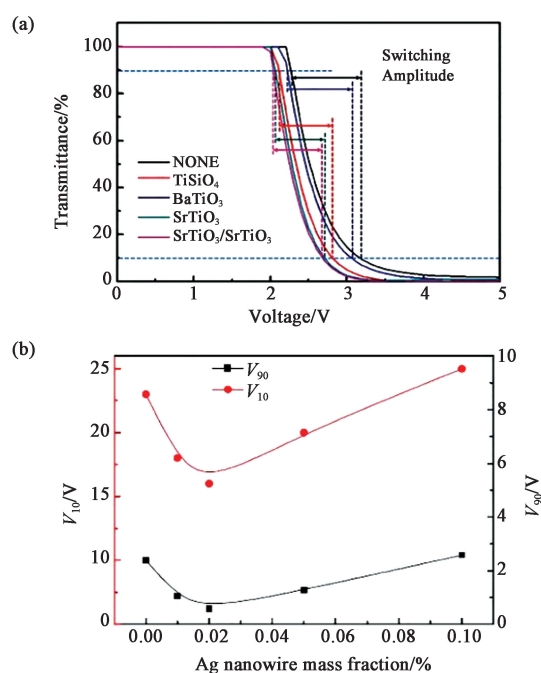


图 4 (a)掺杂 TiSiO_4 、 BaTiO_3 、 SrTiO_3 和 BaTiO_3 / SrTiO_3 粒子液晶膜的电光曲线;(b)不同银纳米线含量的液晶膜的 V_{10} 与 V_{90} 曲线^[66-67]。

Fig.4 (a) V - T characteristics of liquid crystal cells doped with TiSiO_4 、 BaTiO_3 、 SrTiO_3 and BaTiO_3 / SrTiO_3 NPs; (b) Variations of Ag nanowire in voltages for 10% (V_{10}) transmission and 90% transmission(V_{90}).

等提出了一种“一步双稳”(Single-Step Dual Stabilization, SSDS)方法来制备液晶调光膜,通过使用掩模控制聚合区域形成聚合物墙结构,液晶分子以及凝胶被限制在墙内的网格中,改善了液晶膜的光电性能,增强了液晶膜的机械强度。体系中的主要成分为液晶、凝胶剂以及小分子可聚合单体。其中,凝胶剂用于生成胶凝聚合物网络,以稳定液晶分子的取向,而可聚合单体则用于形成坚韧的密封层,保护智能窗,防止液晶内容物流出,如图 5 所示。

通常,PSLCs 是通过紫外光引发单体聚合而形成。但是,过强的紫外光往往会对体系中的某些组分,比如染料分子造成破坏,导致其颜色失真甚至褪色^[71-72]。为了解决这一问题,Yu^[73]等提出了一种热聚合的方法,可有效防止染料因紫外光照而变质,得到的颜色纯正、阻光性能良好的 PSLCs 膜,可用于智能窗以及动态屏幕等领域,如图 6 所示。

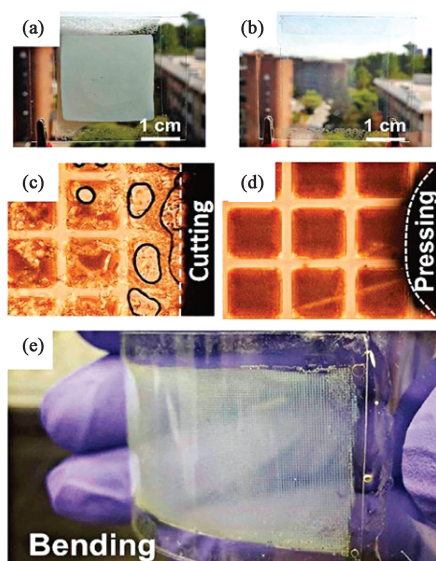


图5 SSDS 液晶盒的宏观散射态(a)和透明态(b)图像; SSDS 液晶盒受剪切作用(c),压力作用(d)时的偏光图片以及受弯曲作用(e)时的实物图片^[70]。

Fig.5 Macroscopic images of the light scattering state (a) and the light transmission state(b); Orthoscopic POM images of the SSDS cells for pressure resistance(c), cutting test(d), and macroscopic image of the bended SSDS cell(e).

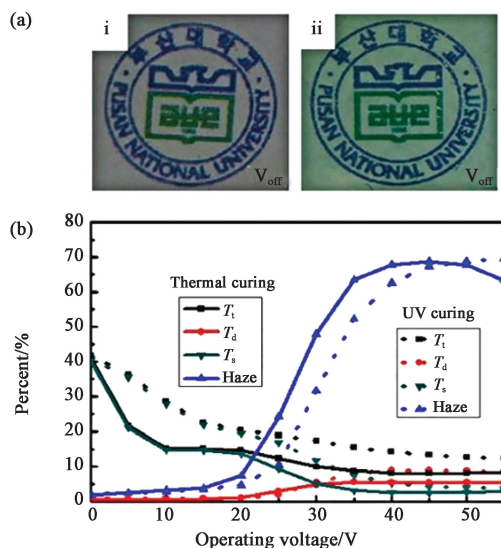


图6 热聚合(i)与UV光聚合(ii)得到的PSLCs的实物照片(a)以及总透射率(T_t)、漫透射率(T_d)、镜透射率(T_s)和雾度(b)^[73]。

Fig.6 (a) Photographs of dye-doped PSLCs cells fabricated by thermal (i) and UV light (ii) and the measured total transmittance(T_t), diffuse transmittance(T_d), specular transmittance(T_s) and haze(b).

2.2 温度响应调光膜

温度响应调光膜因自身的配置较简单,从而使得其制造和维护的成本很低,特别是与电控智能窗相比,不需要添加电极等额外的电力系统和其他部件。此外,其自动响应温度的特点,减少了对开关系统的需求,从而无需消耗外部能量或依赖于人工操作的电气控制^[74-77]。通过感应周围环境热量的变化而改变其光透过率是降低建筑能耗的一种有前途的解决方案,因此温度响应新型智能窗技术吸引了越来越多的科学关注^[78-80]。

PDLCs更易制备大面积的柔性薄膜,但薄膜中的液晶分子无规取向;而PSLCs虽然可以控制其中液晶分子的取向,但所得液晶膜剪切强度弱,难以应用于柔性器件。因此,北京大学杨槐教授课题组采用分步聚合的方法,利用非液晶性聚合单体之间的聚合速率大于液晶性聚合单体的特点,使含有上述两类聚合单体的液晶膜于不同聚合条件下先后形成PDLCs和PSLCs的基础结构,成功研制出一种聚合物分散/稳定液晶的共存体系。该复合体系的液晶膜综合了两者的优点,在具有PDLCs良好力学强度的基础上又兼有PSLCs良好的透光态,并可进一步通过向其体系中掺杂纳米粒子的方法,制得多重响应类型的液晶调光膜,例如:Liang^[81]等通过将甲基丙烯酸氧

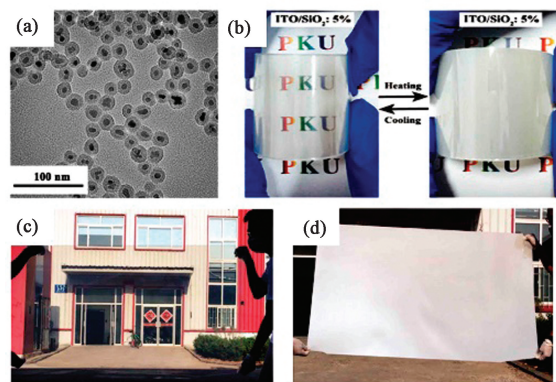


图7 (a)乙醇中的MPTMS改性的ITO/SiO₂纳米粒子的TEM照片;(b)所得调光膜的柔韧性以及工业制得的大尺寸液晶调光膜的(c)透明态及(d)散射态^[81]。

Fig.7 (a) TEM image of MPTMS-functionalized ITO/SiO₂ NCs in ethanol; (b) Flexibility of the as-made smart film; The transmittance state(c) and scattering state(d) of the as-made large scale films.

基丙基三甲氧基硅烷(methacryloxypropyltrimethoxysilane, MPTMS)表面改性的 ITO 粒子掺入聚合物分散/稳定液晶复合体系,利用 ITO 的近红外光遮蔽性,可制得一种大面积的温度-电场双响应体系共存的液晶膜,如图 7 所示。该液晶膜具有良好的力学性能与光学性能,有望作为智能窗器件应用于实际生活。

ITO 粒子具有良好的近红外光区遮蔽作用,但在实际应用场景中,并不总是需要将环境中的红外光过滤掉,因此 ITO 粒子对近红外光不可调

节的阻隔作用不能完全适应人们的需求。二氧化钒粒子作为一种热敏材料,晶体结构会在温度升高到 $68\text{ }^{\circ}\text{C}$ 时由单斜晶系转变为金红石相,相应地,粒子对于近红外光也由高透过率转变为高反射率,更常被用作智能材料,一直受到研究人员的密切关注^[82-84]。因此 Liang^[85] 等通过将钨掺杂的二氧化钒粒子与液晶-聚合物复合体系相结合,制备了一种新型的温度-电场响应液晶膜,如图 8 所示。这项工作充分利用了液晶分子的电场响应性和二氧化钒粒子的温度响应性,使得液晶膜在电场开、关态以及环境高低温情况下,共有 4 种不同的调控模式,在可见光区及近红外光区内实现了智能调控。由于研究中形成的聚合物网络结构同为聚合物分散/稳定液晶共存体系,因此液晶膜在拥有良好的电光性能的同时,也具有良好的耐疲劳性,有望应用于新型智能器件。

Ranjesh^[86] 等报道了一种具有反射波段可调的 PSCLC 智能薄膜,该薄膜可通过温度-电场实现双外场调控,如图 9 所示。利用液晶盒内竖直方向上单体的聚合速率在强紫外光下会有明显差异的现象,使得聚合形成的网络密度产生明显的梯度分布,即体系内胆甾相液晶的螺距也会随之有大范围的分布,由于平面取向的胆甾相液晶会将入射光中一定波长的旋向与自身相同的部分光反射,而反射的区间又取决于液晶的螺距长短。因此,研究中的螺距梯度宽幅分布可以使液晶膜实现宽波调控,且体系中加入的少量紫外光吸收剂可稳定聚合物网络,延长调光膜的使用寿命。

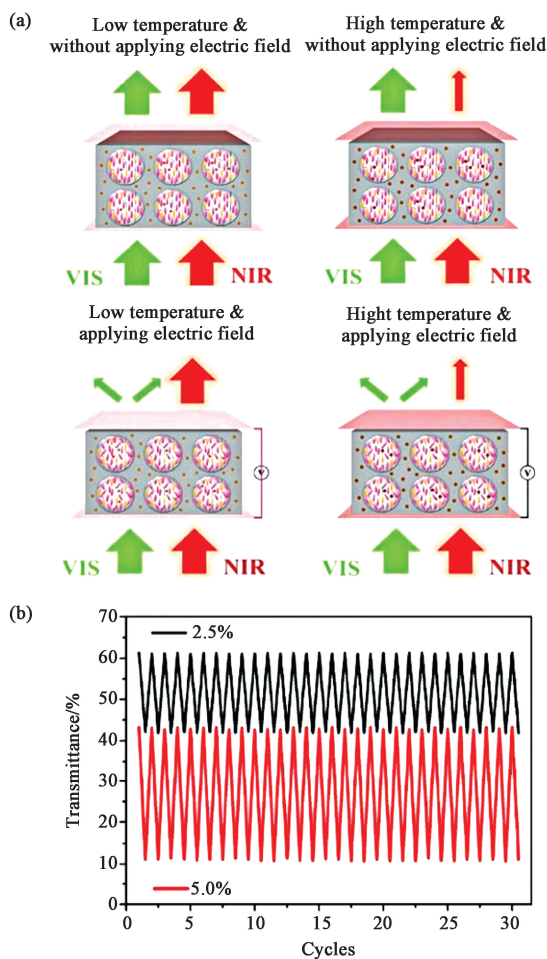
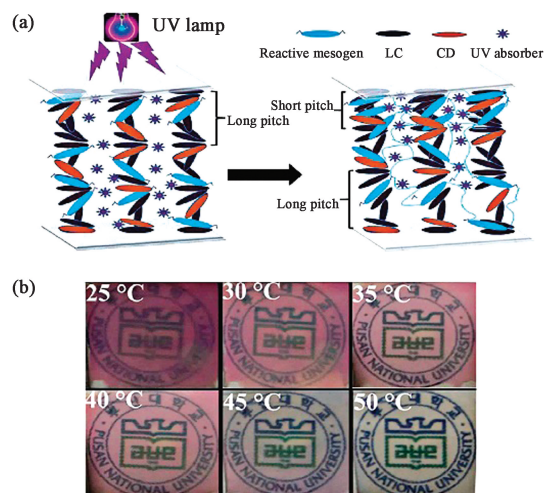


图 8 (a)液晶膜的 4 种不同调控模式;(b)含 2.5% (黑色)和 5.0%(红色)W-VO₂/PVP 纳米粒子薄膜在 1150 nm 处的加热和冷却循环的透光率^[85]。

Fig.8 (a) Four optical modulation modes realized in the hybrid micro-nano composite film; (b) Transmittance of the films containing 2.5% (black) and 5.0% (red) W-VO₂/PVP NCs at 1150 nm during the heating and cooling cycles.



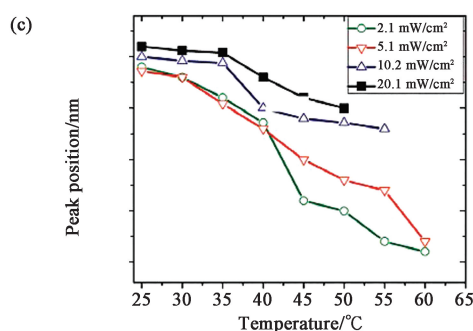


图9 (a)螺距梯度形成机理示意图;(b)PSLCs 膜的温度依赖性;(c)不同聚合光强的 PSLCs 反射峰的位置^[86]。

Fig.9 (a) Schematic representation of the proposed mechanism for the generation of the pitch gradient throughout the cell; (b) Temperature dependence of the cell; (c) Peak position as a function of temperature at different UV intensity.

Zhang^[87]等利用液晶随温度变化的相转变特性以及胆甾型液晶对电磁波的选择反射特性,制得了一种温度响应的 PSCLC 调光膜,如图 10 所示。这种液晶调光膜在低温条件下,只会反射波长较长的红外光;而随着温度的升高,液晶的有序程度降低,CLC 的螺距减小,PSCLC 调光膜的反射波段也因此发生蓝移,从而反射近红外波段的电磁波。与此同时,该 PSCLC 调光膜在可见光波段内还拥有良好的透光度,因此能够在不影响

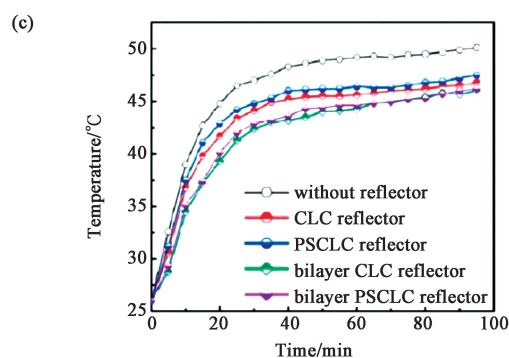
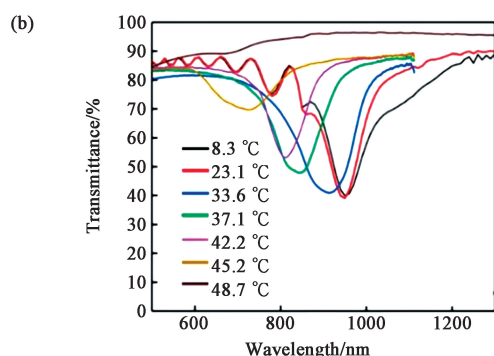
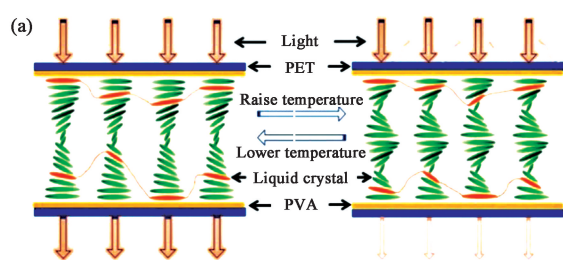


图10 (a)液晶膜反射装置的调控机理;(b)PSCLC 基近红外反射器件的透光率-温度依赖性;(c)无反射装置、加装 CLC 反射装置和 PSCLC 反射装置的密封盒子中的温度变化^[87]。

Fig. 10 (a) Schematics of the temperature-responsive infrared reflective devices based on PSCLC; (b) Temperature-dependent transmission spectra of the flexible infrared reflector based on PSCLC; (c) Temperature changes with time of the thermal insulation box with a CLC reflector, a PSCLC reflector, and without a reflector.

视觉体验的前提条件下阻挡热辐射,起到一定的隔热效果。

2.3 光响应调光膜

由于电控 PSLCs 智能窗在保持其电光性能、实现其使用价值时仍要耗费部分能源,而温控 PSLCs 智能窗的光性能环境调控又不够灵活,因此研究人员也在不断探寻一种更易调控、能源消耗更少的 PSLCs 智能窗,因此,光响应调光膜逐渐引起了各国技术人员的重视。

Kuang^[88]等提出了一种基于偶氮苯基团光热效应的紫外光响应调光膜。研究将具有光响应特性的偶氮基团引入垂直取向层,赋予了液晶膜透光率光调控的性质,如图 11 所示。在初始态,由于垂直取向层的锚定作用,液晶分子呈垂直排列,调光膜为透明态;当受热或者紫外光照射后,取向层结构中的偶氮苯分子发生顺反异构反应,使得液晶分子转变为手征向列相,调光膜呈散射态。这种 PSLCs 调光膜不仅有良好的热/紫外光响应性,还具有良好的可逆性和稳定性,可用作节能智能窗。

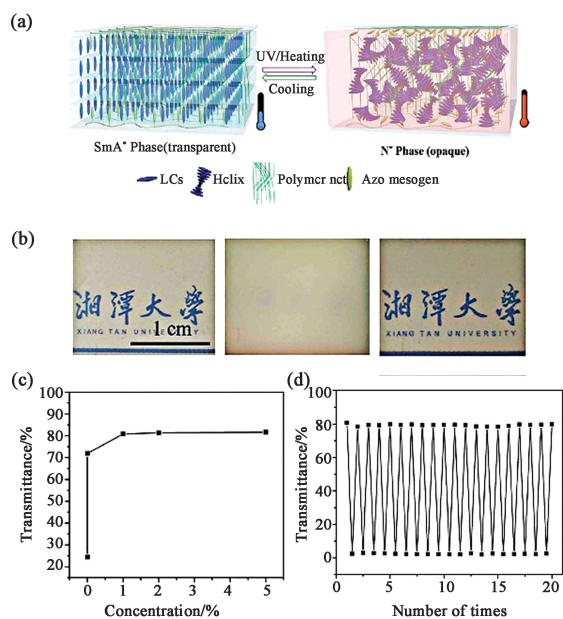


图 11 (a)液晶智能窗的光-热效应示意图;(b)所得 PSLC 膜的各向同性态、手征向列相以及手征近晶相的照片;(c)不同聚合物刷含量的 PSLC 膜的透光率;(d)所得 PSLC 液晶膜的耐疲劳性^[88]。

Fig.11 (a) Scheme of the proposed smart window based on the photo-thermal effect; (b) Photographs of the fabricated PSLCs cells in the Isotropic, N* and SmA* phases; (c) Transmittance values of PSLC cells as a function of the concentration of the polymer brush; (d) Transmittance of PSLC cell under repeated UV and visible irradiation.

程张祥等^[89]利用偶氮苯类分子的光响应性,将偶氮苯分子与 PSLCs 复合得到了一种可进行光调控的智能窗。该智能窗两侧无需设置电极层,聚合物稳定液晶中添加的偶氮苯分子会沿垂直于入射光的偏振方向而排列,使得所得的智能窗在偏振光照射下呈透明状态,而在自然光照射下呈不透明状态,两种状态可通过智能窗表面偏振膜的简单拆装而实现。这种无需电压控制液晶取向的智能窗器件更加节能环保,并且其中的偶氮苯分子还可吸收部分紫外光,提高了液晶层的耐久度,使智能窗的性能更加稳定。

2.4 PSLCs 双稳态调光膜

上述多种液晶膜的光学性能会随着电场的施加与撤除、温度的升高与降低或光强的增大与减

小而发生实时的变化。但在日常生产生活中的某些需要液晶调光膜提供持续稳定的遮光或透光条件应用场景,则需要长时间地施加外场刺激,这无疑会消耗较多能量,也限制了调光膜的使用范围。因此,研究人员开始寻求一种即使撤去外场刺激,光学性能也可长时间保持的液晶调光膜,双稳态液晶膜便逐渐走入了人们的视野。双稳态液晶器件多由胆甾型液晶为主要组成部分^[90-93],只需施加短时间的的外场刺激即可将液晶膜调控至透明态或散射态,而即使随后撤去电场,液晶智能窗仍能保持之前的光学状态不发生变化,可有效实现智能窗的节能作用^[94-97]。

Lee^[98]等报道了一种在近红外光区有反射峰的聚合物稳定双稳液晶调光膜,如图 12 所示。

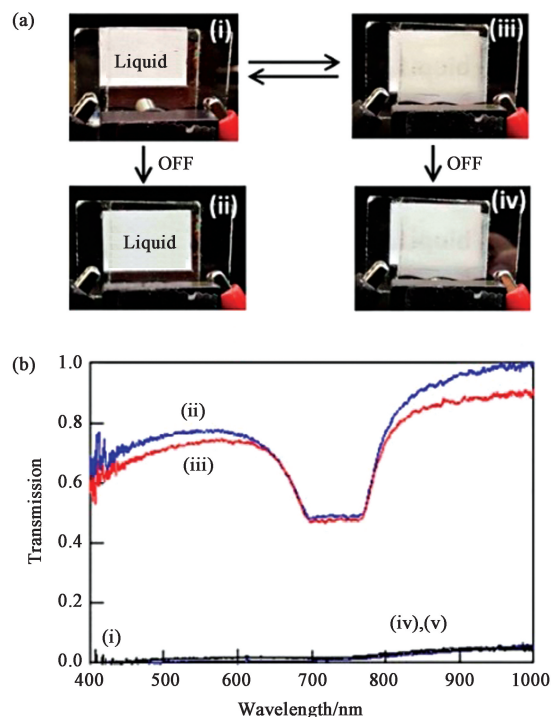


图 12 (a)15 μm 厚的液晶膜在(i) 50 V AC,(ii) 0 V,(iii) 100 V DC 和 (iv) 0 V 电压下的照片;(b)30 μm 厚的液晶膜在(i) 0 V,(ii) 100 V AC,(iii) OFF(0 V);(iv) 45 V DC;(v) OFF(0 V)时的透光率^[98]。

Fig.12 (a) Photographs of samples with 15 μm thickness at (i) 50 V AC, (ii) 0 V, (iii) 100 V DC, and (iv) 0 V; (b) Transmission of samples with 30 μm thickness at (i) 0 V, (ii) 100 V AC, (iii) OFF(0 V), (iv) 45 V DC, (v) OFF(0 V).

所得液晶膜在初始态为散射态,施加 100 V 交流电场后,液晶膜变透明;再次施加一个 45 V 的直流电场,调光膜又能够保持散射态。所得液晶膜既具有 PSLCs 响应速度快的优点,又同时具

备了双稳的特性,在未来有望应用到建筑及交通等领域。

Kim^[99]等将二向色性染料与离子添加剂掺杂于聚合物稳定液晶膜中,改善了液晶膜的光学性能。研究发现初始态的液晶分子在 HTAB 离子表面活性剂的作用下呈垂直排列,当施加电场后,离子扰动液晶体系转变为焦锥织构,调光膜对入射光强烈散射,如图 13 所示。所得液晶膜既具有良好的光学性能,也具有良好的持久性,可作防窥装置使用。

3 总结与展望

基于聚合物稳定液晶的智能调光膜近些年来吸引了科研人员的广泛关注,相关的研究也越来越深入。本文简要介绍了各种外场响应类型的聚合物稳定液晶智能调光膜的制备方法、工作原理。总结了近些年来国内外研究人员在该领域取得的研究进展。相较于聚合物分散液晶,聚合物稳定液晶智能窗的响应条件更加灵活,光学性能也在不断提高,适用范围更加广泛。但是,在器件基板的粘结性、耐久性以及环境稳定性方面还有待进一步提升。另外,应因节能、环保的实际需求,聚合物稳定液晶智能窗的研究重点将会更加向温控、光控以及多重调控等领域拓展。尽管聚合物稳定液晶智能窗还面临上述提到的一些问题,相信在科研工作者的不断努力下,这类聚合物稳定液晶调光膜一定具有宽广的应用前景。

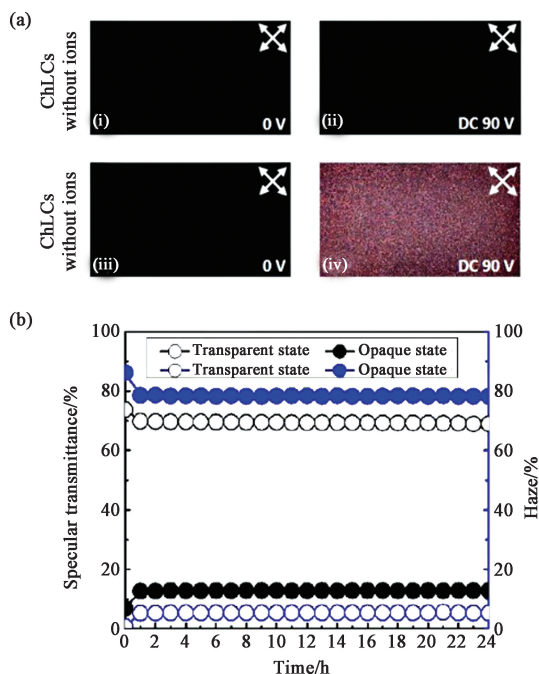


图 13 (a)不含离子添加剂的液晶膜在(i) 0 V, (ii) 90 V 以及含有离子添加剂的液晶膜在(iii) 0 V, (iv) 90 V 时的偏光图像; (b)液晶膜的雾度和透光率随时间的变化^[99]。

Fig.13 (a) POM images of the fabricated CLC cells without ions at (i) 0 V, (ii) DC 90 V or with ions at (iii) 0 V, (iv) DC 90 V; (b) Haze value and specular transmittance vs. time of the fabricated ion-doped CLC cell.

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作者简介:



张艺瑜(1998—),男,山西长治人,硕士研究生,2019 年于北京化工大学获得学士学位,主要从事聚合物稳定液晶调光膜方面的研究。E-mail: 2019210163@mail.buct.edu.cn



郭金宝(1979—),男,黑龙江拜泉人,教授,2008 年于北京科技大学获得博士学位,主要从事液晶及功能高分子材料在显示、传感器及能源等领域的基础和应用方面的研究。E-mail: guojb@mail.buct.edu.cn