Advertisement

Advanced Optical Materials / Volume 1, Issue 6 / p. 417-421

Communication 🔂 Full Access

Electrically Induced Color Changes in Polymer-Stabilized Cholesteric Liquid Crystals

Michael E. McConney, Vincent P. Tondiglia, Lalgudi V. Natarajan, Kyung Min Lee, Timothy J. White, Timothy J. Bunning 💌

First published: 02 May 2013 https://doi.org/10.1002/adom.201300111 Citations: 42

Abstract

Large-scale color changes (100s of nm) in polymer-stabilized cholesteric liquid crystals with a negative dielectric anisotropy are presented. Reflection peak tuning is enabled with DC electric fields through a unique peak splitting behavior. This simple approach can be applied in a variety of photonic applications.



Cholesteric liquid crystals (CLCs) are self-organized selectively reflective materials that are highly promising for active photonic applications including displays, <u>1</u> tunable lasers, <u>2</u> optical storage, <u>3</u>, <u>4</u> and energy-conserving windows. <u>5</u> Dynamic response of the bandgap color, bandwidth, or reflectivity can be induced by exposure to a variety of stimuli including electric fields, heat, and light. <u>6</u> Electrically tunable CLCs are particularly promising, in principle, for reflective display applications <u>1</u> although there are few reports of practical tuning due to difficulties in complex geometries and large electric fields needed to date. Limitations with the tuning range of the peak wavelength have also been observed. This work presents a material

system which exhibits large range tuning under small applied electric fields, enabled by the polymer stabilization of a CLC formulation composed of a negative dielectric liquid crystal host.

The selective reflection (color) of CLCs is a manifestation of the periodic helical organization of the phase, which when macroscopically organized in the Grandjean texture satisfies the condition for Bragg reflection.1, 7 The central wavelength of the reflection bandgap is defined as:

$$\lambda_0 = \bar{n} P$$

(1)

where P is the pitch length of the helical twist of the director and \overline{n} is the average refractive index of the liquid crystal. Assuming a constant pitch, the CLC reflection bandwidth, $\Delta\lambda$, is defined as:

$$\Delta \lambda = \Delta n P$$

(2)

where Δn is the birefringence of the CLC. CLCs are typically formulated by doping a nematic LC with an enantiomeric excess of a chiral dopant. The length of the helicoidal pitch can be tailored by varying the chiral dopant concentration ([c]) through the following relationship,

$$P = \frac{1}{HTP * [c]}$$

(3)

where HTP, the so-called helical twisting power, is a measure of the ability of a chiral molecule to twist a nematic LC.

A large portion of the prior demonstrations of color tuning of CLCs have employed interdigitated electrodes. While novel and potentially useful in reflective displays, interdigitation of the electrodes naturally give rise to spatially varying optical properties across the cell (non-uniform coloration and reflectivity), governed by the complex interplay between the electric field pattern and the CLC.<u>8-10</u> Furthermore, focal conic scattering domains can readily form

near the electrodes, although this has been partially eradicated by polymer stabilization of the CLC.11 Comparatively fewer reports of electric-field tuning of CLCs employ conventional cell architectures (e.g. cells coated with transparent conductive oxides such as ITO), as opposed to interdigitated electrodes. Many of these reports employ planarly aligned CLCs composed from a nematic LC with negative dielectric anisotropy $(-\Delta\varepsilon)$, wherein application of an electric field across the cell will not cause molecular reorientation. Limited tuning can occur simply through defect annealing that depends strongly on the initial quality of the cell. This approach has been used effectively to switch a CLC (mirrorless) laser on and off.12 CLCs with positive dielectric anisotropy $(+\Delta\varepsilon)$ can tune in response to DC fields through tilting of the helical axis.13-15 Simoni and co-workers pioneered a mechanical based tuning technique involving piezoelectric compression of a cholesteric liquid crystal.16, 17 A similar electromechanical approach utilizes DC fields to electrostatically deform the substrates towards one another, which subsequently compresses the pitch in conditions of strong anchoring, thereby resulting in blue tuning.18 This effect takes advantage of the planar alignment boundary conditions and enables pitch distortions of up to 20% in either direction depending on the cell design.

There are several other notable examples of electrically induced color and refractive index changes in CLCs, <u>19-27</u> but the best example to date has been reported by Kent Optronics, Inc. They have reported electrically induced reflective peak tuning of up to 300 nm at low fields. <u>28</u>, <u>29</u> Their presented mechanism involves a high cross-linked, unresponsive polymer that maintains a static pitch while the low molecular weight LC molecules rotate in response to a field. In other words, the response is mediated by electrically induced effective refractive index changes. This system, based on positive dielectric materials, has also been engineered to enable large peak width broadening as well.

This manuscript presents electrically tunable color changes in a $-\Delta\epsilon$ polymer stabilized cholesteric liquid crystal (PSCLC), where modest DC field strengths can induce significant color tuning. The cells are prepared by filling a planar aligned cell with a mixture containing a $-\Delta\epsilon$ NLC, chiral dopant, photo-initiator, and chiral monomer (specific details in the Experimental Section). The mixture is then photopolymerized by exposing the sample to UV light. **Figure 1**a shows the reflection spectra at various electric field strengths taken from the positive electrode of the cell. A plot of the reflection wavelength as a function of the electric field strength is shown in Figure 1b. Above the threshold voltage (>1 V/µm) the color undergoes a red shift that is linearly dependant with increasing field strengths (~35 nm/(V/µm)). The color (reflection wavelength) can be reversibly and repeatably modified up to 50%. The data presented in Figure 1 was obtained by increasing the field strength by 0.33 V/µm every second. The color change apparent in the cell is depicted in Figure 1c as well as in MOVIE1 (Supporting Information).

Figure 1

Open in figure viewer **PowerPoint**

Large range color tuning observed upon application of DC fields. a) The reflection spectra at DC electric fields strengths ranging from 0–9 V/ μ m. b) A plot of the central reflection peak position (nm) versus the applied DC field strength (V/ μ m). c) Photographic images of color change of the cell as DC field strength is increased from 0–8 V/ μ m. All reflection spectra were collected with the positive electrode of the cell facing the white light source and reflection probe of the spectrometer.

The response time of the cells, examined in **Figure 2**, were measured by exposing samples to a step function in the field strength, while the reflection wavelength position was monitored with time. A plot of the central reflection wavelength taken from the positive electrode as a function of time is plotted for field strengths of 1–8 V/µm, as shown in Figure 2a. The response times were on the order of tens of seconds and the maximum tuning rate was 65 nm/s. After the reflection color of the cell stabilized at a given applied field strength, the field was reduced (step-function) to 0 V and the relaxation time was measured, as shown in Figure 2b. The relaxation time of the PSCLC can be significantly improved by momentarily reversing the polarity of the DC field. Below 9 V/µm the samples the tuning behavior was very repeatable. The repeatability of the cell is evident in Figure 2 because the initial tuning slopes and starting wavelengths are the same throughout the test. Above 9 V/µm the sample repeatability is compromised and at fields >10 V/µm the samples will irreversibly fail.

Figure 2

Open in figure viewer **PowerPoint**

a) Temporal response of the change in reflection peak position for DC fields strengths ranging from 1–8 V/µm (switching on). b) Temporal response of the restoration of the reflection peak position upon removal of DC field (switching off). All reflection spectra summarized here were collected with the positive electrode of the cell facing the white light source and reflection probe of the spectrometer.

To understand the fundamental drivers behind the observations, we explored the response of CLC mixtures before and after polymerization, with positive and negative dielectric nematic liquid crystal hosts, and upon application of AC rather than DC fields (**Figure 3**). As plotted in Figure **3**, the response of the CLC before polymerization to DC electric fields induces slight blue-shifting tuning (~25 nm at 6 V/µm). This behavior, very different than the response after polymerization, is attributed to defect annealing and enhanced order parameter. **12** Figure **3**b

contrasts the response of the typical polymer stabilized - $\Delta\epsilon$ CLC cell to the response of a cell with a polymer stabilized + $\Delta\epsilon$ CLC. Usually a homogeneous + $\Delta\epsilon$ CLC will undergo a molecular reorientation in response to a field across the cell, but in this case the sample shows little change due to the strong polymer stabilization. The - $\Delta\epsilon$ CLC reflection wavelength changes by ~300 nm in response to 8 V/µm, whereas the + $\Delta\epsilon$ CLC reflection wavelength changes by only ~15 nm (20 times less). Application of an AC field (Figure <u>3</u>c) also results in little response, which indicates that the tuning is related to ion migration as opposed to dipole reorientation.

Figure 3

Open in figure viewer **PowerPoint**

Comparison of the response of CLC mixtures to applied electric fields (DC unless specified). a) Response of R811/AMLC0026/RMM691 mixture before and after polymerization. b) Response of polymer stabilized CLC mixtures employing a negative dielectric anisotropy nematic liquid crystal host (AMLC0026, $-\Delta\epsilon$) and a positive dielectric anisotropy host (E7, $+\Delta\epsilon$). c) Response of polymer stabilized R811/AMLC0026/RMM691 mixture to applied AC (100Hz) and DC fields. All reflection spectra were collected with the positive electrode of the cell facing the white light source and reflection probe of the spectrometer.

Figure <u>4</u> presents the reflection spectra taken from both the negative electrode side and the positive electrode side, as well as the corresponding transmission spectra. The data presented in Figure 4 was taken from a thinner cell (10 μ m) with less scatter than in Figure 1 (15 μ m cell). The transmission spectra did not depend on the polarity direction, thereby indicating that the inherent polymer properties are homogenous through the cell thickness (see Supporting Information). On the other hand, a distinct difference in the reflection spectra exists depending on the polarity of the applied field. The reflection spectrum originate from a finite depth (several µm) from the sample surface due to the sample scatter. This finite sampling depth was used to provide information about the CLC pitch profile through the cell thickness. Upon slowly ramping the field strength from 0 to 2 V/µm, the main reflection peak from the positive electrode side at 550 nm splits into two distinct peaks with the main peak shifting to 570 nm and a much smaller remnant peak shifting to 490 nm. At 2 V/µm the same peak splitting is seen in the reflection spectra from the negative electrode side, but the main peak and the remnant peak have a more similar percent reflection. Therefore, at 2 V/µm the reflection spectra indicate that the smaller remnant peak is closer to the negative electrode side and the main peak with higher reflection is shifted to the positive electrode side. Below the saturated point of 50% reflection (>~10 pitches), the percent reflection is also an indication of the number of pitches at a particular pitch length. The main peak has a higher percent reflection in both of the spectra taken at 2 V/µm indicating that there are more pitches associated with the main peak

compared to the remnant peak. There is also significantly more volume associated with the main peak than the remnant peak because the pitch length is longer.

Figure 4

Open in figure viewer **PowerPoint**

Transmission, T, spectra at various electric field strengths are presented in the first row. The second row and third row present reflection, R, spectra at various electric field strengths taken from the negative side and positive side, respectively. The bottom row presents a schematic of the PSCLC under applied field and an empirically predicted plot of the relative pitch length versus the distance from the negative electrode.

As the voltage is increased beyond 2 V/µm the remnant peak continues to blue shift out of band and the % reflection goes to zero. The magnitude of the tuning rate ($\Delta\lambda/\Delta E$) of the remnant peak on the negative electrode side is more than double the magnitude of the main red-tuning peak on the negative electrode side (see supporting information). The percent reflection of the remnant peak from the negative electrode side also decreases with field strength about 10 times more than the main peak. The reflection from the positive electrode side of the cell shows the large red-shifted tuning reported earlier in the work. These results (i.e. a distribution of pitch across the cell gap) are very similar to electric field induced symmetrical broadening samples that also involve applying DC electric field to a polymer stabilized - $\Delta \epsilon$ CLC.<u>30</u> In this prior report, the bandwidth of the reflection notch broadens nearly symmetrically on both the red and blue band edges upon application of DC field. The prior examination of symmetrical broadening were in weakly stabilized (1–5% polymer) PSCLCs with an achiral diacrylate monomer whereas those here were from a strongly stabilized (10–20 wt%) polymer) PSCLC formed from a commercial chiral monomer mixture. Both systems show a reddistortion to the positive electrode side and a blue-distortion to the negative electrode side. The difference presented here is that the pitch change through the thickness is described with a higher order function instead of a simple linear function. Empirical observations support a logarithmic profile of pitch versus thickness from the negative electrode as is schematically represented in the bottom row of Figure 4. For clarity, it should be emphasized that the thicker sample presented in Figure 1 had the same non-linear pitch distribution. The reflection spectra from the positive electrode presented in Figure <u>1</u> did not contain a remnant peak due to the finite sampling depth caused by sample scatter.

Based on these studies,<u>30</u> we propose that the reflection tuning observed is caused by an electrophoretic based mechanism involving charge trapping on the surface of the polymer. This postulate is supported by recent impedance measurements of the symmetrical broadening

7/27/2021

samples showing a correlation between sample threshold voltage and a sharp rise in the sample impedance, thereby indicating that the sample response onset occurs after the free charges in the low molecular weight LC migrate to the electrodes. It is well-known that liquid crystal mixtures contain low concentrations of ionic impurities (10¹¹–10¹³ ions/cm³)31-34 and that these mobile charges can have dramatic effects on LCs in response to DC fields.35 Strong evidence has also recently been presented that the photopolymerized mesogenic monomers in polymer stabilized liquid crystals act as strong ion trapping systems and significantly decrease the number of free charges in the liquid crystal. <u>36</u> We postulate that the polymer trapped charges are attracted to the negative electrode in the presence of a uniform field which results in a distortion of the polymer network local density across the cell thickness. Due to surface anchoring effects of the polymer fibrils, the LC molecules follow the distorted pitch of the polymer. An even distribution of trapped charges on the polymer surface through the thickness of the cell would predictably lead to a linear deformation of the polymeric pitch, consistent with the symmetrical broadening behavior reported previously. The non-linear behavior observed here is not well understood, but given the large deformation of the polymer network, logically some inter-polymer fibril ionic repulsion could occur thereby leading to a non-linear pitch distribution towards the longer pitch. Elucidating the mechanistic details are the subject of current studies.

In conclusion, a new approach to large scale color changes using reflection tuning of a PSCLC with an applied DC electric field is presented. The reflection wavelength red tunes to the positive electrode side, while a small remnant peak blue tunes out of band to the negative electrode side. The reflection wavelength tuning occurs over 100's of nm while maintaining good contrast at relatively low electric field strengths. Evidence indicates that the effect is caused by the movement of locally trapped charges on the polymer surface in response to a DC electric field. The peak splitting mechanism is a simple and ubiquitous phenomena in polymer stabilized CLC's with a $-\Delta\varepsilon$ host exposed to DC fields. This simple approach to large scale reflection tuning has important implications for the field of tunable photonic materials.

Experimental Section

Cell Preparation: A polyimide solution was prepared by mixing 8 mL of PI2555 polyimide (HD Microsystems), 32.5 mL of *N*-methyl pyrrolidone and 9.1 mL of 1-methoxy-2-propanol. This mixture was filtered through a 0.45 µm filter (Pall, Acrodisc PSF syringe filter) onto ITO coated glass. The mixture was spun coat (APH, spin 150) by ramping up to 1500 rpm for 15 s followed by spinning at 3000 rpm for 1 min. The coated ITO-glass was baked at 200 °C for 30 min. This process was repeated for a second piece of ITO-coated glass. Then the polyimide films were rubbed to achieve a planar oriented anchoring layer. Then the glass pieces were glued together with spacers to form an empty cell.

Sample Preparation: Cells were filled with a mixture containing 18.2 wt% chiral monomer RMM691 (Merck), 15.5 wt% chiral dopant R811(Merck), 0.4% Irgacure-369 initiator and 65.9% – $\Delta\epsilon$ achiral nematic AMLC0026 (n_{ave} = 1.565, Δ n = 0.150 (589 nm, 20 °C), $\Delta\epsilon$ = -5.0 (1 kHz, 25 °C) (Alpha Micron). The mixture had a peak reflection wavelength ~560 nm and thus a pitch of ~360 nm. The cells were capillary filled with the mixture at elevated temperature (~80 °C) and were exposing to 30 mW cm⁻² of UV light (365 nm, Coherent) for 3 min at room temperature, thereby polymerizing the monomer.

Optical Measurements: Reflection and transmission spectra were taken simultaneously with two USB2000+ vis-NIR spectrometers (Ocean Optics). Custom Labview software was used to apply the electric field and simultaneously acquire the spectrum.

Acknowledgements

The authors wish to thank Dr. Christopher Bailey and Prof. Deng-ke Yang for insightful discussions. We gratefully acknowledge funding from the Air Force Office of Scientific Research and the Materials and Manufacturing Directorate of the Air Force Research Laboratory. MEM gratefully acknowledges the National Research Council for fellowship support.

Supporting Information

As a service to our authors and readers, this journal provides supporting information supplied by the authors. Such materials are peer reviewed and may be re-organized for online delivery, but are not copy-edited or typeset. Technical support issues arising from supporting information (other than missing files) should be addressed to the authors.

Filename	Description
adom201300111-sup-0001-S1.docx 2.2 MB	Supplementary
adom201300111-sup-0001-S2.wmv 476.2 KB	Supplementary

Please note: The publisher is not responsible for the content or functionality of any supporting information supplied by the authors. Any queries (other than missing content) should be directed to the corresponding author for the article.

References

https://onlinelibrary.wiley.com/doi/full/10.1002/adom.201300111

1 S. T. Wu, D. K. Yang, *Reflective Liquid Crystal Displays*, Wiley, New York, NY, 2001. Google Scholar

2 H. Coles, S. Morris, *Nat. Photonics* 2010, **4**, 676. Crossref | CAS | Web of Science® | Google Scholar

3 W. Haas, J. Adams, G. Dir, *Chem. Phys. Lett.* 1972, **14**, 95. Crossref | CAS | Web of Science® | Google Scholar

4 N. Tamaoki, *Adv. Mater.* 2001, **13**, 1135. Wiley Online Library | CAS | Web of Science® | Google Scholar

5 M. Addington, D. Schodek, *Smart Materials and Technologies for the Architecture and Design Professions*, Architectural Press, Oxford, 2005. Google Scholar

6 T. J. White, M. E. McConney, T. J. Bunning, *J. Mater. Chem.* 2010, **20**, 9832. Crossref | CAS | Web of Science® | Google Scholar

7 P.-G. de Gennes, J. Prost, *The Physics of Liquid Crystals*, Oxford University Press, Oxford, 1995. Crossref | Google Scholar

8 Z. Li, P. Desai, R. B. Akins, G. Ventouris, D. Voloschenko, *Proc. SPIE-Int. Soc. Opt. Eng.* 2002, **4658**, 7. Crossref | Web of Science® | Google Scholar

9 H. Xianyu, S. Faris, G. P. Crawford, *Appl. Opt.* 2004, **43**, 5006. Crossref | CAS | PubMed | Web of Science® | Google Scholar

10 M. J. Escuti, C. C. Bowley, G. P. Crawford, S. Zumer, *Appl. Phys. Lett.* 1999, **75**, 3264. Crossref | CAS | Web of Science® | Google Scholar

11 S.-Y. Lu, L.-C. Chien, *Appl. Phys. Lett.* 2007, **91**, 131119. Crossref | CAS | Web of Science® | Google Scholar

12 T.-H. Lin, H.-C. Jau, C.-H. Chen, Y.-J. Chen, T.-H. Wei, C.-W. Chen, A. Y. G. Fuh, *Appl. Phys. Lett.* 2006, **88**, 061122.

Crossref | CAS | Web of Science® | Google Scholar

13 R. Bartolino, A. Ruffolo, F. Simoni, N. Scaramuzza, *Nuovo Ciment. B* 1982, **1**, 607. Crossref | Google Scholar 14 F. Simoni, G. Cipparrone, R. Bartolino, *Mol. Cryst. Liq. Cryst.* 1986, **139**, 161. Crossref | CAS | Web of Science® | Google Scholar

15 N. Scaramuzza, C. Ferrero, V. Carbone, C. Versace, *J. Appl. Phys.* 1995, **77**, 572. Crossref | CAS | Web of Science® | Google Scholar

16 C. Umeton, R. Bartolino, G. Cipparrone, F. Simoni, *Appl. Optics* 1988, **27**, 210. Crossref | CAS | Web of Science® | Google Scholar

17 C. Umeton, R. Bartolino, G. Cipparrone, F. Xu, F. Ye, F. Simoni, *Mol. Cryst. Liq. Cryst.* 1987, **144**, 323. Crossref | Web of Science® | Google Scholar

18 C. A. Bailey, V. P. Tondiglia, L. V. Natarajan, M. M. Duning, R. L. Bricker, R. L. Sutherland, T. J. White, M. F. Durstock, T. J. Bunning, *J. Appl. Phys.* 2010, **107**, 013105.
Crossref | CAS | Web of Science® | Google Scholar

19 W. Hu, H. Zhao, L. Song, Z. Yang, H. Cao, Z. Cheng, Q. Liu, H. Yang, *Adv. Mater.* 2010, **22**, 468. Wiley Online Library | CAS | PubMed | Web of Science® | Google Scholar

20 S. S. Choi, S. M. Morris, W. T. S. Huck, H. J. Coles, *Adv. Mater.* 2010, **22**, 53. Wiley Online Library | CAS | PubMed | Web of Science® | Google Scholar

21 S. S. Choi, S. M. Morris, W. T. S. Huck, H. J. Coles, *Adv. Mater.* 2009, **21**, 3915. Wiley Online Library | CAS | Web of Science® | Google Scholar

22 H. Xianyu, T.-H. Lin, S.-T. Wu, *Appl. Phys. Lett.* 2006, **89**, 091124. Crossref | CAS | Web of Science® | Google Scholar

23 S. S. Choi, S. M. Morris, W. T. S. Huck, H. J. Coles, *Soft Matter* 2009, **5**, 354. Crossref | CAS | Web of Science® | Google Scholar

24 J. Chen, S. M. Morris, T. D. Wilkinson, H. J. Coles, *Appl. Phys. Lett.* 2007, **91**, 121118. Crossref | CAS | Web of Science® | Google Scholar

25 W. Hu, L. Zhang, H. Cao, L. Song, H. Zhao, Z. Yang, Z. Cheng, H. Yang, L. Guo, *Phys. Chem. Chem. Phys.* 2010, 12, 2632.
Crossref | CAS | PubMed | Web of Science® | Google Scholar

26 L. De Sio, S. Ferjani, G. Strangi, C. Umeton, R. Bartolino, *Mol. Cryst. Liq. Cryst.* 2012, **553**, 147. Crossref | CAS | Web of Science® | Google Scholar 27 G. Carbone, P. Salter, S. J. Elston, P. Raynes, L. De Sio, S. Ferjani, G. Strangi, C. Umeton, R. Bartolino, *Appl. Phys. Lett.* 2009, **95**, 011102. Crossref | CAS | Web of Science® | Google Scholar

28 H. Yu, B. Y. Tang, J. Li, L. Li, *Opt. Express* 2005, **13**, 7243. Crossref | CAS | PubMed | Web of Science® | Google Scholar

29 L. Li, J. Li, B. Fan, Y. Jiang, S. M. Faris, *Proc. SPIE* 1998, **3560**, 33. Crossref | CAS | Web of Science® | Google Scholar

30 V. T. Tondiglia, L. V. Natarajan, C. A. Bailey, M. M. Duning, R. L. Sutherland, D. Ke-Yang, A. Voevodin, T. J. White, T. J. Bunning, *J. Appl. Phys.* 2011, **110**, 053109. Crossref | CAS | Web of Science® | Google Scholar

31 N. Sasaki, *Jpn. J. Appl. Phys.* 1998, **37**, 6065. Crossref | CAS | Web of Science® | Google Scholar

32 T. Nakanishi, T. Takahashi, H. Mada, S. Saito, *Jpn. J. Appl. Phys.* 2002, **41**, 3752. Crossref | CAS | Web of Science® | Google Scholar

33 H.-Y. Chen, K.-X. Yang, W. Lee, *Opt. Express* 2004, **12**, 3806. Crossref | PubMed | Web of Science® | Google Scholar

34 L. Lu, V. Sergan, P. J. Bos, *Phys. Rev. E* 2012, **86**, 051706. Crossref | CAS | Web of Science® | Google Scholar

35 L. M. Blinov *J. Phys. Colloques* 1979, **40**, C3. Google Scholar

36 J.-H. Son, S. B. Park, W.-C. Zin, J.-K. Song, *Liq. Cryst.* 2013, DOI: 10.1080/02678292.2012.757372 . Crossref | PubMed | Google Scholar

Citing Literature

 \sim

Download PDF

About Wiley Online Library

Privacy Policy Terms of Use Cookies Accessibility

Help & Support

Contact Us Training and Support DMCA & Reporting Piracy

Opportunities

Subscription Agents Advertisers & Corporate Partners

Connect with Wiley

The Wiley Network Wiley Press Room

Copyright © 1999-2021 John Wiley & Sons, Inc. All rights reserved