Multiparameter Laser Performance Characterization of Liquid Crystals for Polarization Control Devices in the Nanosecond Regime

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The interactions of liquid crystals (LC's) with polarized light have been studied widely and have spawned numerous device applications, including the fabrication of optical elements for high-power and large-aperture laser systems. Such devices have numerous advantages that include scalability to large apertures, cost effectiveness, high optical quality and contrast, broad angular tolerance, and laser-induced–damage thresholds (LIDT's) for optimized materials at 1054 nm of >30 J/cm^2, 3 J/cm^2, and 1 J/cm^2 at 1-ns, 10-ps, and 600-fs pulse durations, respectively.[1,2] Evaluation of the LIDT of LC materials has been performed historically in long-path-length LC cells (50 to 100 μm) to gain an understanding of the LC material's behavior under exposure to high-energy laser pulses without competing physicochemical interactions with surface-anchoring layers and conditions (LC elastic constants, boundary molecular tilt angle, alignment materials chemistry and application methods[2,3]). Although useful for screening LC materials by chemical class to determine general laser survivability, such long-path-length testing gives very little insight on how the LC's LIDT may be affected in device applications where the LC molecules are constrained in a monodomain alignment state induced by contact with substrates bearing a polymer alignment layer (e.g., wave plates, mirrors, and beam shapers). In such cases, variations in optical behavior as a function of laser beam polarization due to molecular orientation, chemical interactions, or generation of electric-field enhancements in the LC material are a distinct possibility.[4–6] This summary reports on the first study of the nanosecond-pulsed LIDT's dependence on incident polarization for several optical devices employing nematic and chiral-nematic LC's oriented by surface alignment layers. Accelerated lifetime testing was also performed to characterize the ability of these materials and devices to maintain their performance under multi-pulse irradiation with increasing laser fluence at both 1053 nm and 351 nm (Ref. 7).

Figure 1 shows generic molecular structures of LC components with differing degrees of π-electron density (saturation) that were evaluated for their multipulse laser damage behavior in optical element configurations typically used in high-peak-power lasers (e.g., circular polarizers and wave plates), where the LC molecular director, which defines the average long-range orientation of the LC molecular axes in the bulk, is constrained to adopt a monodomain or nearly monodomain orientation.

A pulsed nanosecond laser system operated at either its fundamental wavelength (1053 nm) or the third harmonic (351 nm) was used along with a novel detection system employing a polarization-sensitive camera to detect both the onset of performance degradation and classical LIDT of several LC mixture compositions in both circular polarizers and wave-plate device geometries. These measurements were designed to explore a "laser-induced functional threshold" (LIFT), defined as a reduction in one or more system-defined, key device functional parameters (e.g., transmission, reflection, birefringence, polarization rotation, contrast) that may occur at fluences lower than those required to produce the visible and permanent evidence of material modification typically defined as laser-induced damage. The point at which the value of LIFT drops below a system-defined tolerance metric is taken as the LIFT "trigger point." For the purposes of this study, the LIFT trigger pointy was a reduction in transmission to <98% (Ref. 7).

Testing of these LC materials at 1053 nm and 351 nm showed that their LIDT behavior depends significantly on the incident polarization state for laser light encountering the input surface of the LC test device at near-normal incidence (7°). For LC circular polarizer devices, the LIDT varied as a function of incident circular-polarization handedness by a factor of 30% to 80% for a given sample (Fig. 2). It appears that an angular dependence of high-peak-power LIDT on incident polarization in LC materials

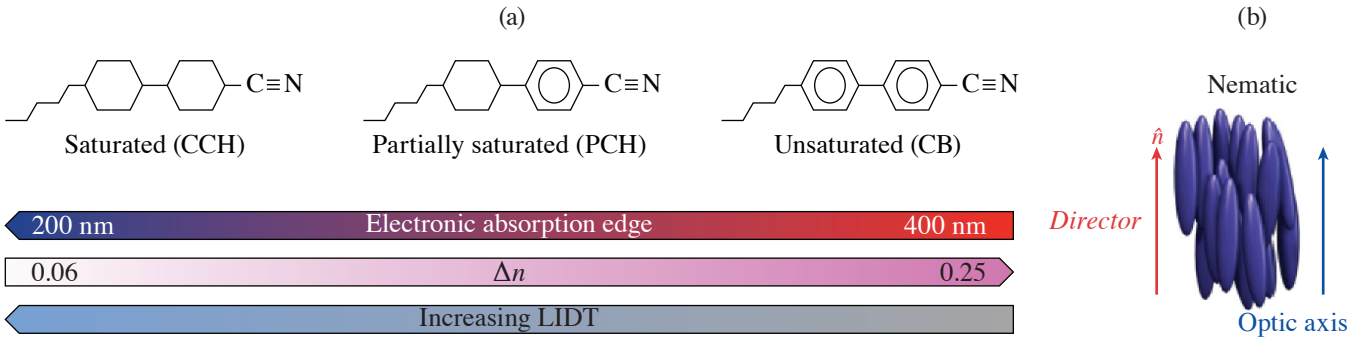

Figure 1
(a) Molecular structures for the three classes of LC compounds evaluated and a graphical representation of the dependence of optical absorbance, birefringence, and laser damage with respect to these classes. (b) Molecular ordering in the nematic LC phase. For this class of LC materials, both the LC director and the optic axis are parallell to the molecular axis.

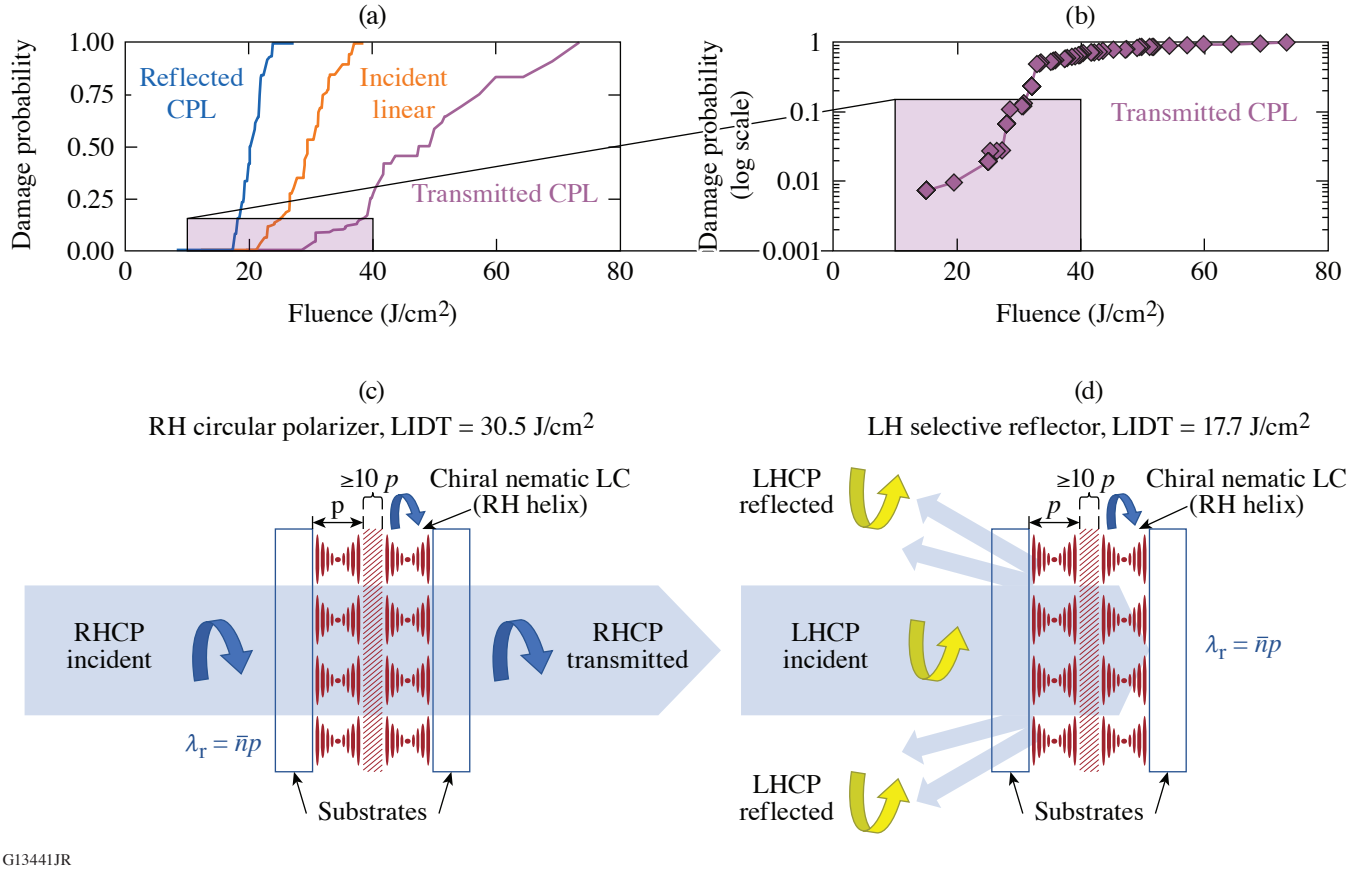

Figure 2
(a) Damage probabilities for the chiral-nematic LC circular polarizer/isolator device as a function of 1053-nm, 1.4-ns laser fluence and incident polarization; (b) damage probabilities for transmitted circularly polarized light pulses incident on the device at low fluence [corresponding to the inset in Fig. 2(a)]. The data, plotted on a logarithmic scale, represent an additional 250 sites of 1-on-1 damage data collected by line-scanning the sample; [(c),(d)] the interaction of circularly polarized light of opposite handedness on the LC structure, along with the representative LIDT thresholds. For (c), incident circular polarized light with the same twist sense as the LC helix (right-handed) is transmitted, whereas in (d) for the same device, incident circular polarization of the opposite handedness (left-handed) is selectively reflected due to Bragg scattering. A cell thickness of at least ten pitch lengths (p), indicated by the area filled with diagonal slashes near the center of the cell, is required to observe these effects with sufficient magnitude for device applications.

has not been reported previously. The results suggest that multipulse functionality was best preserved in LC devices having the highest degree of saturation.

Certain compositions of saturated, UV transparent nematic LC mixtures evaluated in a wave-plate geometry displayed remarkable robustness in LIFT testing at 351 nm, with one CCH-based LC mixture (LLE1202) being able to survive as many as 1000 1-ns pulses at 2 J/cm^2 (5-Hz repetition rate) before displaying any significant change in its functional performance (Fig. 3). The LIDT was seen to vary as a function of input polarization by 30% to 80% within the same device, while the multi-pulse LIFT depends on irradiation conditions such as laser fluence and wavelength.

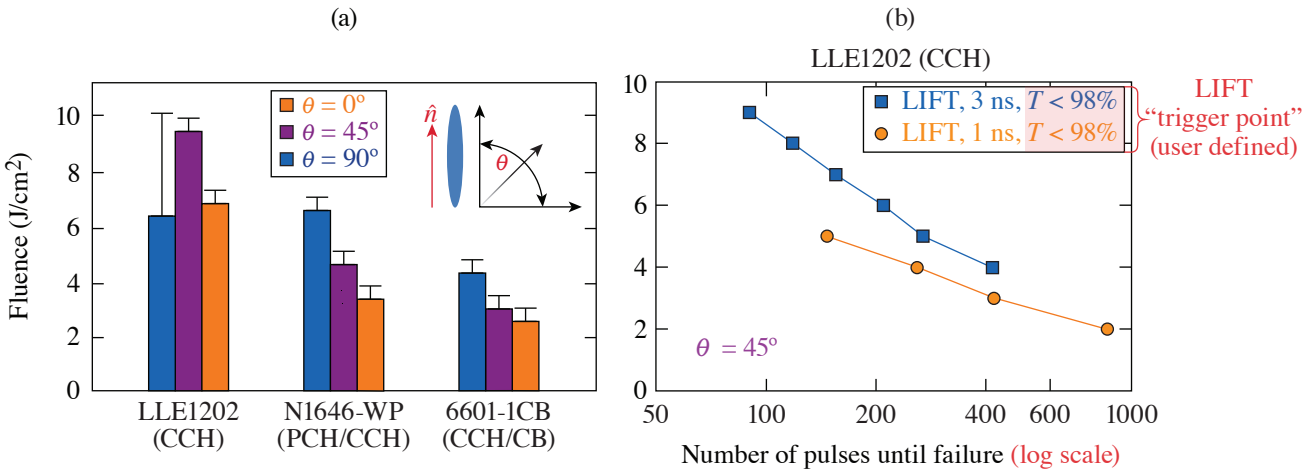

Figure 3
(a) LIDT at 351-nm, 1-ns pulse duration as a function of incident linear polarization angle with respect to the LC director. Uncertainty bars extend to the nominal 0% and 100% damage probability fluences. (b). LIFT results for LLE1210 at 351 nm for both 1-ns and 3-ns laser pulses delivered at a 5-Hz repetition rate. The high saturation of this CCH-based LC material allows it to withstand nearly 1000 pulses at 2 J/cm^2. The inset in (a) shows the orientation of the LC director with respect to the incident laser polarization.

These promising results highlight the potential of this class of LC materials in nanosecond-regime, high-peak-power lasers such as OMEGA for applications as polarization control and polarization-smoothing optics. Another distinct advantage of LC optics is that in the event they do sustain damage, they can be refurbished and reinstalled in a laser system with a relatively low cost of materials and effort. The results also illustrate the necessity of taking the molecular structure and electron delocalization of LC mesogens into account when designing new materials for such emerging applications.

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