Section 4
ADVANCED TECHNOLOGY DEVELOPMENT

4.A Liquid-Crystal Laser-Blocking Filters

In various laser applications, situations often arise which require selective optical filtration. Optical elements which exhibit extremely low transmittance at the specific laser wavelength, λ_0, and high transmittance at other wavelengths are required to filter optical radiation incident, for example, upon ultraviolet (UV) diagnostics or infrared (IR) thermal-imaging systems. Laser goggles for eye protection of personnel constitute another area where laser-blocking notch filters are useful. Figure 26 gives an example of spectral transmission characteristics of a generic notch filter.

Some of the design and performance goals for a laser-blocking notch filter operating at a wavelength of λ_0 are as follows:

1) attenuation at λ_0 greater than 10^3;
2) transmittance away from λ_0 better than 85%;
3) ease of alignment, or broad angular acceptance;
4) a device that is compact, lightweight and inexpensive; and
5) adequate laser-damage resistance.

High in-band attenuation and high out-of-band transmittance are required to provide optical sensors with protection against lasers without sacrificing the ability to detect background radiation. Angular insensitivity to laser radiation and light weight are important for personnel protection devices such as laser goggles.

Absorbing glasses or dye/plastic filters, thin-film interference filters,[1] and holographic filters[2] are examples of materials technologies that

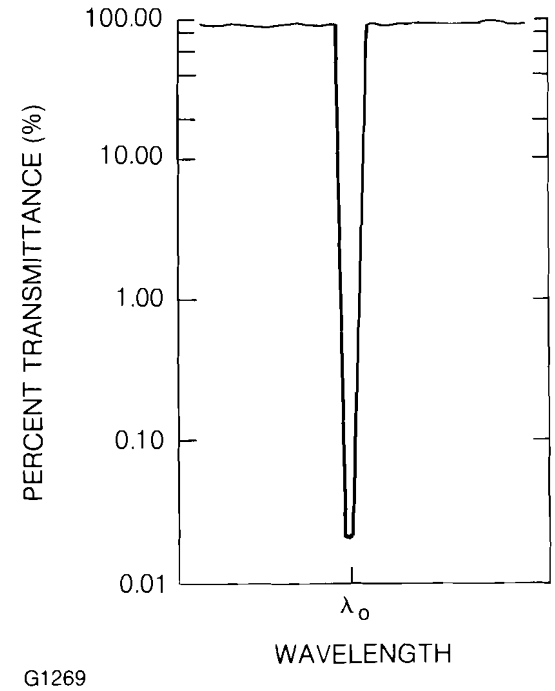

Fig. 26
Spectral characteristics of a laser-blocking notch filter. Laser radiation at $\lambda = \lambda_0$ is attenuated, whereas background optical radiation at shorter and/or longer wavelengths is transmitted with negligible loss.

have been used to construct notch filters. None of these approaches has succeeded in meeting all of the performance goals listed above. Liquid crystals offer an alternative method for constructing laser-blocking notch filters which approaches more closely the concept of a perfect notch filter.

The cholesteric class of liquid-crystal compounds exhibits the unusual property of selective reflection.[3] (The reader is referred to the article on liquid crystals in Volume 5 of the LLE Review, and the figures therein, for a more complete discussion of the structure and properties of cholesteric liquid crystals.) The basis for this effect resides in the spontaneous, helical alignment exhibited by cholesteric molecules on a microscopic scale. Through the use of suitable preparation techniques to induce helical alignment over macroscopic distances, liquid-crystal cells can be fabricated which act as nearly perfect circular polarizers. Optical radiation incident upon a cell is totally reflected if its polarization sense matches the chirality, or helicity, of the cholesteric compound.[4] (Unlike the case for standard reflection from a dielectric at near-normal incidence, the phase of the light reflected by the liquid-crystal cell is *not* shifted by 180°.) The orthogonal polarization is transmitted with negligible loss. The effect is strong, and a fluid layer no more than a few tens of microns in thickness is required. The wavelength selectivity of this effect arises because optical radiation interacts with the cholesteric structure only if the wavelength λ_0 satisfies the equation:

$$\lambda_0 = n_n p \qquad (1)$$

where n_n is the average refractive index of the cholesteric, and p is a measure of the pitch of the molecular helix. The selective reflection effect may be shifted from the UV to the IR by creating an appropriate mixture of cholesteric compounds with different values of intrinsic pitch.

Notch filters may be constructed from cholesteric liquid crystals by stacking together two liquid-crystal cells filled with fluids possessing opposite chiralities, which have been tuned to the same wavelength, λ_o.[5] The concept is shown in Fig. 27. At the wavelength for selective reflection, the device performs as a nearly perfect pair of crossed circular polarizers, blocking incident laser radiation. Optical radiation at wavelengths away from λ_o is transmitted through the filter with negligible attenuation.

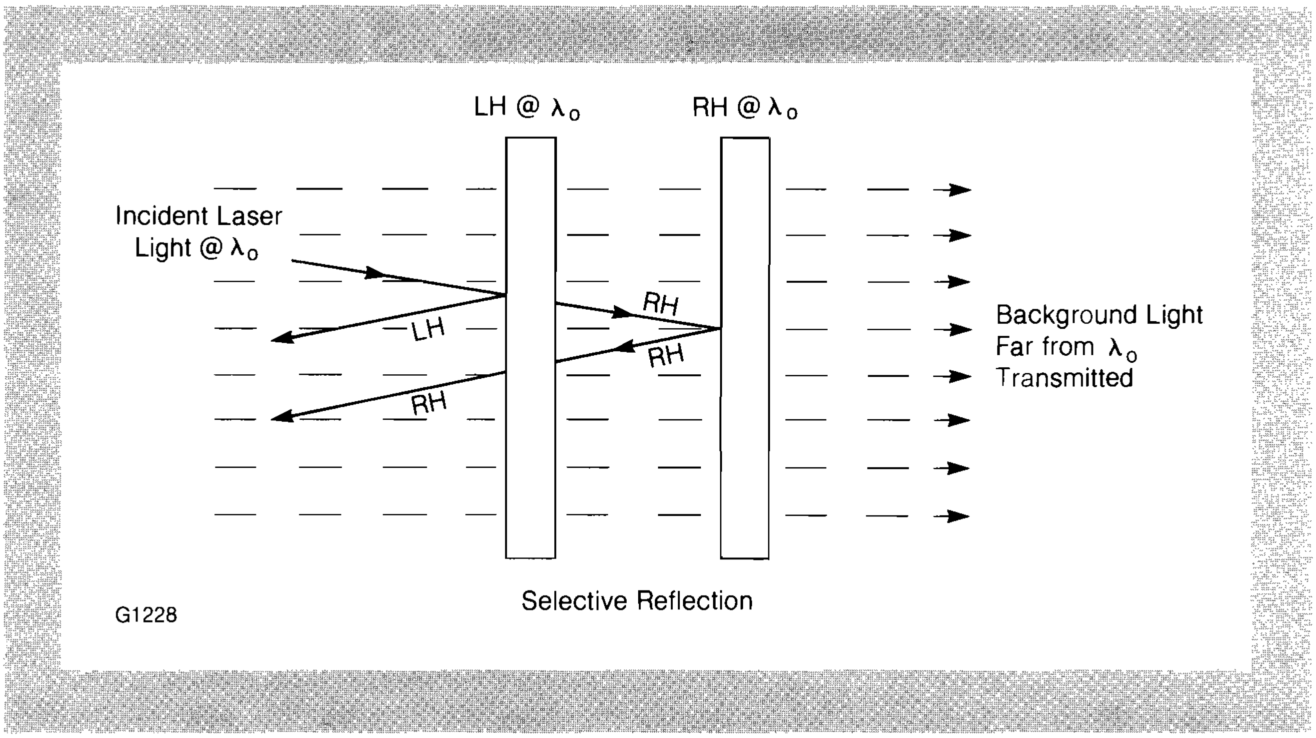

Fig. 27
Liquid-crystal laser-blocking filter concept. The filter consists of two liquid-crystal cells. Each cell is filled with a cholesteric compound tuned to exhibit selective reflection at the laser wavelength, λ_o. Because the mixtures have opposite senses of helical alignment (one is left-handed whereas the other is right-handed), the device acts as a pair of crossed circular polarizers to block the transmission of laser radiation at λ_o. Background optical radiation at $\lambda \neq \lambda_o$ is transmitted through the filter with negligible attenuation, due to the wavelength-selective nature of the effect.

We have constructed and characterized a number of liquid-crystal laser-blocking filters at LLE. The 38-mm-diameter substrate material for our experiments is fused silica. Liquid layer spacers are cut from "Mylar" films that vary in thickness from 6 to 36 μm. Cells are sealed with either quick-drying epoxy or UV-curing cement. Left-handed and right-handed mixtures of appropriate pitch are prepared from commercially available nematic and cholesteric compounds without additional purification. (Nematics may be thought of as liquid crystals with infinite pitch. Refer to Volume 6 of the LLE Review for a discussion of this class of liquid-crystal materials.) Table 1 lists some of these compounds, their helical sense, and the short-wavelength boundary (discussed below). All mixtures are chemically and photochemically stable, and are relatively insensitive to temperature.

TYPE	MATERIAL (source)	MESOPHASE RANGE, °C	ΔN @ λ = 589 nm	CHIRALITY (handed-ness)	SHORT WAVELENGTH LIMIT, nm (tight pitch constraint)
Nematic	ROTN-701 (HL[a])	-10 to +60.5	0.150	∞	
	ZLI-1167 (EM[b])	+32 to +83	0.060	∞	
	ZLI-1646 (EM)	-7 to +60	0.080	∞	
	S-1236 PCH (HL)	40[c]	0.133	∞	
	NM-820303 (ALX[d])				
Cholesteric	CB-15 (EM)			RH	
	C-15 (EM)			LH	
	COC-Cholesteryl Oleyl Carbonate (EK[e])			LH	
	CN-Cholesteryl Nonanoate (EK)			LH	
	CO-Cholesteryl Oleate (EK)			LH	
	CAA-Cholesteryl Amyl Alcohol (ALX)			RH	
	CEC-Cholesteryl Ethyl Carbonate (S[f])			LH	
Commercial Mixtures	NM-109-15 (ALX)			LH	
	NM-021008 (ALX)			RH	
LLE Mixtures	NM109-15 + CN			LH	> 390
	NM109-15 + CEC			LH	> 390
	NM109-15 + COC			LH	> 385
	NM-021008 + CB-15			RH	> 400
	NM-021008 + CAA			RH	> 450
	NM-820303 + CO			LH	> 400
	XLI-1167 + CB-15			RH	> 385
	ROTN-701 + BA-15			RH	> 430

a Hoffman LaRoche, Nutley, New Jersey
b EM Chemicals, Hawthorne, New York
c preserves nematic order upon cooling to 4° C
d American Liquid Xtal Chemical Corp., Kent, Ohio
e Eastman Kodak Company, Rochester, New York
f Sigma Chemical Co., St. Louis, Missouri

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Table 1 Liquid-crystal materials for notch-filter fabrication.

Cary 14 spectrophotometer scans of notch filters fabricated for several laser wavelengths are shown in Fig. 28. Blocking ratio measurements performed on these cells using laser ratiometry with lock-in detection indicate that extinctions in excess of 10^3 can be achieved in the visible and near-infrared regions for fluid layers 11 μm thick. The width of the selective reflection peak is given as

$$\Delta\lambda_{FWHM} = \frac{\Delta n_n}{n_n} \lambda_o \qquad (2)$$

where Δn_n is the optical birefringence of the mixture. The notch-filter bandwidth may be adjusted from approximately 20 nm to 120 nm in the visible and near-infrared regions by choosing liquid-crystal compounds which maximize or minimize the optical birefringence.

The angular sensitivity of the selective reflection effect may be calculated from the formula[6]

$$\lambda = \lambda_o \left[\sin^{-1}\left(\frac{1}{n_n} \sin\theta\right)\right] \qquad (3)$$

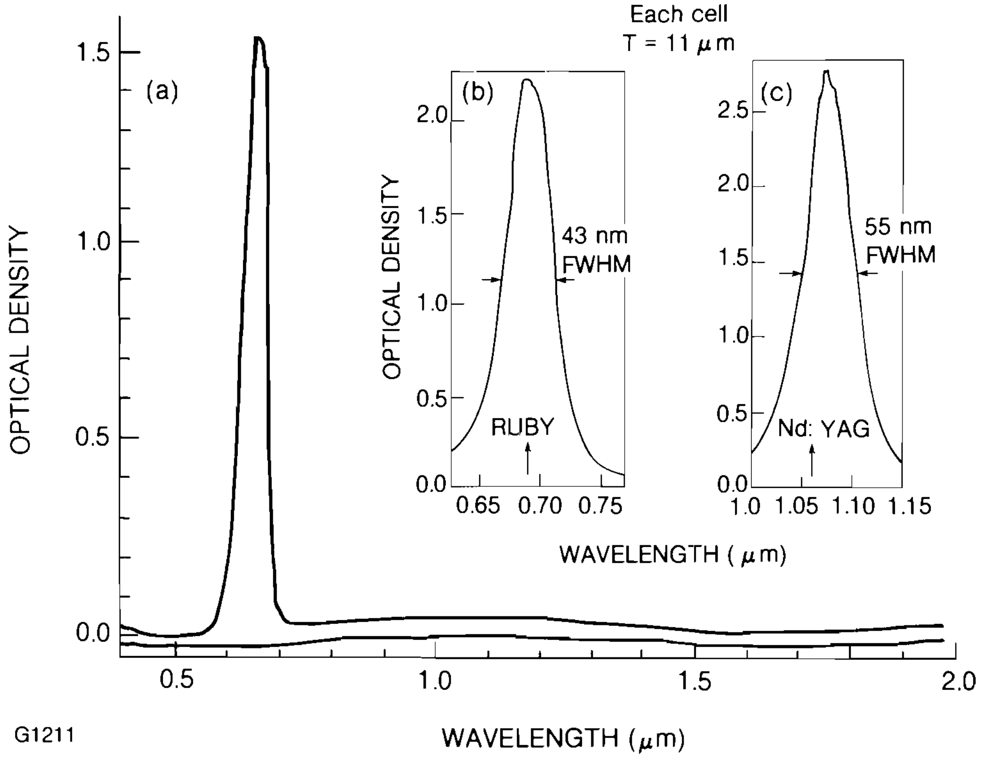

Fig. 28
Cary 14 spectrophotometer scans of notch filters. Each filter is composed of two cells whose fluid-layer thickness is 11 μm. Composition tuning of λ_0 allows the peak for selective reflection to be adjusted to (a) doubled Nd:YAG at 532 nm, (b) ruby at 694 nm, and (c) Nd:YAG at 1064 nm.

In this formula it is assumed that the angles of incidence and observation, θ, are equal. Figure 29 demonstrates how the selective-reflection wavelength peak shifts as a function of θ according to Eq. 3. The tendency for the peak-to-shift toward shorter wavelengths as θ increases may be incorporated into the design of notch filters to reduce their angular sensitivity further. Filters may be fabricated with λ_0 peaks at normal incidence which are several percent longer than the laser wavelength being blocked. As is demonstrated in Fig. 30, the non-normal incidence blocking capability for these detuned filters is enhanced over that of tuned filters without a significant degradation in normal incidence performance. An increased acceptance angle of $\pm 15°$ at a blocking extinction ratio of 10^3 has been demonstrated.

We are currently determining the factors which limit the use of liquid crystals as notch filters over the optical spectrum. The major impediment to notch-filter construction in the UV appears to be our inability to induce a sufficiently tight (or short) pitch by using the compounds listed in Table 1 to shift λ_0 to wavelengths below 385 nm. Optical absorption does not become a problem for the most transmissive materials until a wavelength of 310 nm is approached. Average internal transmittance in the infrared between 2.5 and 5 μm for cells 50 μm thick is better than 90% for phenylcyclohexane compounds; the transmittance approaches 80% for the cyanobiphenyl K-15 in the thermal-imaging band between 8 and 12 μm.[7] Useful trans-

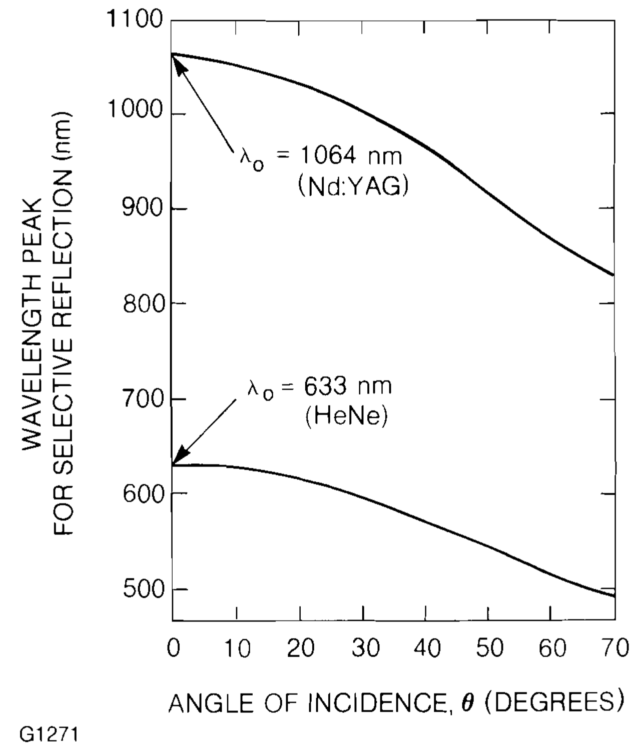

Fig. 29
Shift in selective-reflection peaks versus angle of incidence. The curves are calculated from Eq. 3 for single cells tuned to λ_0 = 1064 nm and λ_0 = 633 nm at normal incidence.

mission in the infrared extends beyond 16 μm. The laser-damage threshold of these compounds is of the order of 20 GW/cm^2 (50 ps, λ = 1054 nm) or 2 J/cm^2 (750 ps, λ = 1054 nm). It is therefore possible to consider liquid-crystal notch filters for use in blocking most gas and solid-state lasers operating from the ultraviolet through the infrared region.

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