# High-speed analog achromatic intensity modulator

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We report what is to our knowledge the first implementation of a broadband analog intensity modulator composed of two chiral smectic liquid-crystal half-wave retarders. A reflection-mode intensity modulator employing a single active device has also demonstrated achromatic transmission. A quantitative theory for chromatic compensation is presented. By optimum selection of liquid-crystal retardance and orientation, intensity transmission is uniform throughout the visible. The chiral smectic liquid-crystal devices used in the implementation are capable of switching in less than 20 $\mu$s.

Broadband high-speed light values have numerous applications, including spectroscopy, camera shutters, and displays. The intensity modulator presented here was independently suggested by Anderson *et al.*[1] and by Sharp.[2] In Ref. 1 qualitative predictions on the behavior of a broadband intensity modulator were presented. Here we provide a quantitative theory for chromatic compensation and include experimental results for what we believe to be the first implementation of a broadband analog intensity modulator based on chiral smectic liquid-crystal retarders.

The transmission-mode achromatic intensity modulator shown in Fig. 1 employs two identical active half-wave plates between crossed polarizers. The active material is chiral smectic A (SmA*) liquid crystal, which provides intensity modulation by means of analog molecular rotation about the device normal.[3] Commercially available SmA* materials exhibit switching speeds of the order of 20 $\mu$s but are limited to a tilt-angle range of less than $\pm 12°$ at room temperature.[4] However, the cascading of two SmA* half-wave retarders of 11.25° tilt angle provides ample rotation to change the polarization of incident light by as much as 90°. Moreover, the dual modulator can be made wavelength insensitive in the visible by means of chromatic compensation.

The intensity transmission of the modulator can be analyzed directly by use of the Mueller calculus.[5] The output Stokes vector $\mathbf{S}_o$ containing the power transmission function is derived according to the equation

$$\mathbf{S}_o(\lambda, \theta_1, \theta_2) = \mathbf{P}_x \mathbf{Q}(\lambda, \theta_1, \theta_2) \mathbf{P}_y \mathbf{S}_i \,, \qquad (1)$$

where $\mathbf{S}_i$ is the Stokes vector for the input source, $\theta_1$ and $\theta_2$ give the orientations of the retarders with respect to the input polarization, $\mathbf{Q}$ is the Mueller matrix describing the active elements, and $\mathbf{P}_x$ and $\mathbf{P}_y$ are $\hat{x}$- and $\hat{y}$-oriented polarizers, respectively. Taking the source to be $\hat{y}$ polarized, with unity power spectral density, we see that the first element of the output Stokes vector represents the intensity transmission function. Substitution of the appropriate Mueller matrices into the above equation yields the transmission function

$$T(\lambda, \theta_1, \theta_2) = \frac{1}{2}(1 - q_{22}) \,, \qquad (2)$$

where $q_{ij}$ are the elements of the Mueller matrix $\mathbf{Q}$. For a modulator consisting of two linear retarders this matrix is given by

$$\mathbf{Q}(\lambda, \theta_1, \theta_2) = \mathbf{W}(\Gamma, \theta_2) \mathbf{W}(\Gamma, \theta_1) \,. \qquad (3)$$

Here the $\mathbf{W}$'s represent the Mueller matrices for the SmA* half-wave retarders having their optic axes oriented at $\theta_1$ and $\theta_2$ with respect to the input polarization, as shown in Fig. 1. The chromatic retardance of the active elements, $\Gamma$, is given by

$$\Gamma(\lambda) = \pi \frac{\Delta n(\lambda)}{\Delta n(\lambda_0)} \frac{\lambda_0}{\lambda} \,, \qquad (4)$$

where $\lambda_0$ is the half-wave retardance wavelength and $\Delta n$ is the dispersive liquid-crystal birefringence. Let $\Gamma = \pi + \delta$, where $\delta$ is the wavelength-dependent departure from the ideal half-wave retardance.

Multiplication of the matrices in Eq. (3) gives

$$q_{22} = \sin^4(\delta/2) + \cos^4(\delta/2)\cos[4(\theta_1 - \theta_2)] + \sin^2(\delta/2)\cos^2(\delta/2)[\cos(4\theta_1) + \cos(4\theta_2)] \,. \qquad (5)$$

With ideal half-wave retarders the active structure functions as a pure polarization rotator. The rotation depends on only the difference between the orientations of the optic axes and is independent of the absolute orientations. However, transmission at other wavelengths depends critically on the absolute orientations as well. By a recasting of the orientations in terms of a difference and a mean orientation this dependence can be clearly demonstrated by the following:

$$\alpha = \left(\frac{\theta_1 - \theta_2}{2}\right), \qquad \alpha_0 = \left(\frac{\theta_1 + \theta_2}{2}\right). \qquad (6)$$

An off state (null in the power transmission) can be obtained for any $\alpha_0$ only when the optic axes are crossed (the structure appears isotropic), giving $\theta_1 = \alpha_0 + 45° - \alpha$, and $\theta_2 = \alpha_0 - 45° + \alpha$.

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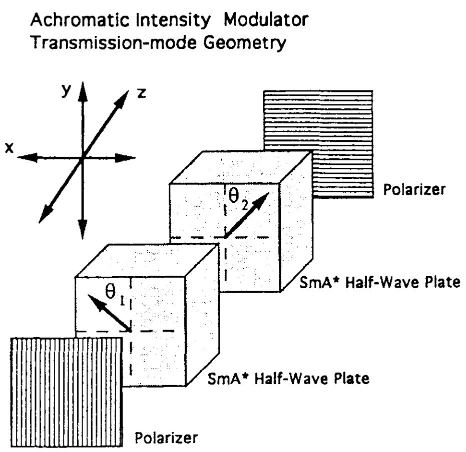


Fig. 1. Schematic for a broadband analog intensity modulator based on a dual SmA* polarization rotator. The angles $\theta_1$ and $\theta_2$ are the absolute orientations of the retarder optic axes with respect to the incident $\hat{y}$-polarized light.

Substitution of Eqs. (6) into Eq. (5) simplifies the intensity transmission function of Eq. (2), as follows:

$$T(\lambda, \alpha_0, \alpha) = \sin^2(4\alpha) - \sin^2(\delta/2)\sin^2(4\alpha) - (1/2)\sin^2 \delta \sin^2(2\alpha) \times [\cos(4\alpha) + \cos(4\alpha_0)]. \quad (7)$$

Chromatic compensation centers around minimizing the loss that is due to $\delta$ in the fully on state ($\alpha = 22.5°$). By examination of the above equation this occurs in general for $\alpha_0 = \pm 45°$. Substituting this orientation into Eq. (7), we obtain the achromatic transmission function

$$T(\lambda, \alpha) = \sin^2(4\alpha) - \sin^2(\delta/2)\sin^2(4\alpha) + \sin^2 \delta \sin^4(2\alpha). \quad (8)$$

The transmission equation consists of the ideal term $[\sin^2(4\alpha)]$ followed by the sum of two chromatic terms. Physically the orientations have been selected such that the second retarder doubles the polarization rotation of the first while suppressing the ellipticity induced by the first. In Eq. (8) the transmission is ideal at $\alpha = 0$ and has a loss in transmission of $\sin^4(\delta/2)$ for the extreme tilt condition ($\alpha = 22.5°$). At intermediate tilts chromatic compensation occurs that provides a substantially flat output spectrum.

Figure 2 demonstrates the theoretical advantage of the dual SmA* modulator over that of a single half-wave retarder. The bandwidth for a 3% loss for the on state of the dual modulator is greater than 200 nm, whereas for a single half-wave retarder it is 74 nm. This is because the dual modulator has a fourth-order wavelength-dependent loss term, whereas the single retarder has a second-order loss term.

Figure 3 compares the theoretical (solid curves) and experimental (dashed curves) output transmission spectra of the dual modulator for linearly polarized light parameterized by the difference angle $\alpha$. Although a few representative values of $\alpha$ are shown, the intensity modulation is analog throughout this range. In both cases the transmission spectrum is nearly flat for each value of $\alpha$ over a 250-nm band.

The simulation used to obtain the theoretical results assumed half-wave retarders at a design wavelength of 520 nm. The broadband intensity modulator used to obtain the experimental results was built with two SmA* liquid-crystal devices employing British Drug House 764E electroclinic material designed as zero-order half-wave retarders at a wavelength of 520 nm (Ref. 4) (1.6-$\mu$m gap). These devices were parallel aligned with polyvinyl alcohol on indium tin oxide-coated substrates. As shown in Fig. 1, the two retarders were oriented to tilt in opposite directions and placed between crossed polarizers. The structure was illuminated with a tungsten-filament source. Electric fields varying from −25 to +25 V/$\mu$m were applied to the devices to change the molecular tilt angle and hence the parameter $\alpha$.

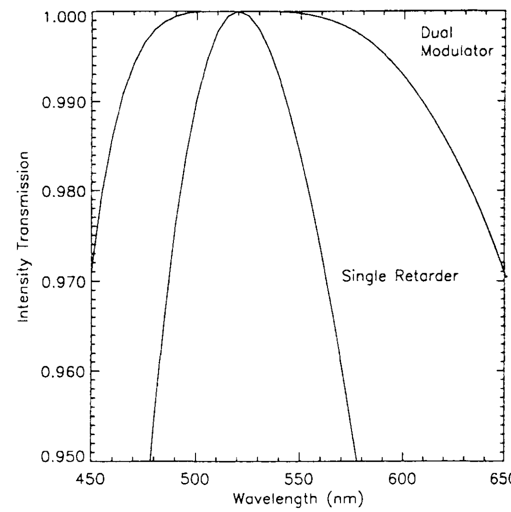


Fig. 2. Theoretical comparison of the bandwidth of the on state of the dual SmA* modulator with the transmission of a single SmA* half-wave retarder between crossed polarizers and oriented at 45° with respect to the incident polarization.

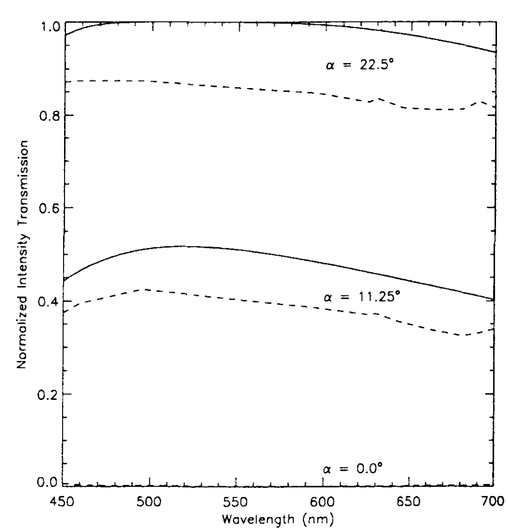


Fig. 3. Comparison of theoretical (solid curves) and experimental (dashed curves) transmission spectra for the analog intensity modulator parameterized by the difference angle $\alpha$.

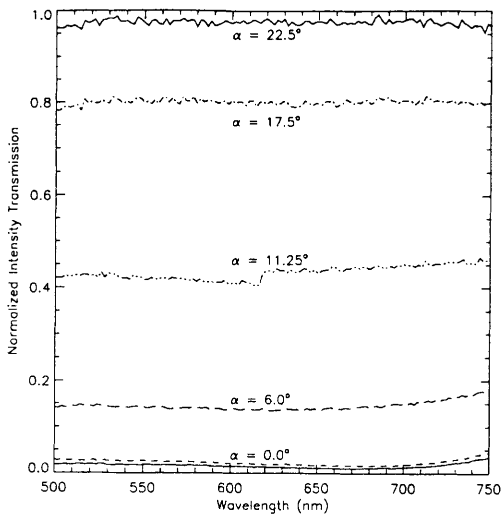


Fig. 4. Experimental transmission spectrum for the reflection-mode analog intensity modulator with a single SmA* device and a compound achromatic quarter-wave retarder. Normalized intensity measurements are parameterized by the difference angle $\alpha$.

Experimental results compare well with theoretical predictions. The transmission intensity for the on state ($\alpha = 22.5°$) should ideally be unity. However, Fresnel losses at the (noncoated) interfaces of the devices and transparent electrode losses result in peak transmission between 85% and 90% for the experimental implementation. If these loss mechanisms are set aside, the measurements are within the experimental error of the theoretical predictions. The spectral contrast of the dual-modulator implementation is approximately 1000:1 over the 250-nm bandwidth, where spectral contrast is defined as the ratio of the maximum to minimum intensities at a given wavelength.

Achromatic intensity modulation by use of a single SmA* device can be achieved with a reflection-mode geometry consisting of a polarizer, an SmA* retarder, a passive quarter-wave retarder, and a mirror. This geometry was suggested by the authors of Ref. 1. However, their design called for a zero-order quarter-wave retarder, which limits the theoretical bandwidth because of its chromatic nature. We have implemented the structure, using an achromatic quarter-wave retarder consisting of three layers of stretched polymer. The passive achromatic quarter-wave retarder and the mirror serve to rotate the polarization leaving the liquid-crystal retarder on the initial pass. This changes the coordinate system so that the reflected optical field encounters the SmA* device with its optic axis reoriented, which is analogous to the function of the second half-wave retarder of the dual modulator discussed above.

The experimental transmission spectrum of polarized light for the reflection-mode achromatic intensity modulator parameterized by $\alpha$ is shown in Fig. 4. The solid curve near the bottom of the figure is the response of the quarter-wave retarder in the absence of the liquid-crystal device. The dashed curve immediately above that is the transmission of the off state. This results were normalized for Fresnel losses producing an on state transmission of 95%. The response was highly achromatic, varying only a few percent over a bandwidth of 250 nm. The contrast ratio for this configuration was nominally 50:1.

In summary, we have reported the implementation of a broadband analog intensity modulator with a wavelength range of 250 nm. The transmission-mode intensity modulator, composed of two SmA* liquid-crystal half-wave retarders, has a contrast ratio of 1000:1. The off state is nearly ideal, and the on state exhibits a maximum 6% variation in transmission from 450 to 700 nm. We can achieve a simpler implementation in the reflection mode by employing a single electroclinic device, a passive achromatic quarter-wave plate, and a mirror. Results for the reflection mode device indicated highly achromatic behavior over a bandwidth of 250 nm in the visible and a contrast ratio of 50:1.

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