

HN22 sheet polarizer, an inexpensive infrared retarder

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The popular sheet polarizer, Polaroid HN22, has been measured to be a nearly half-wave retarder in the 3.6–5.4- μm spectral band with a transmittance of approximately 20%. Tuning of the retardance value between 60° and 260° has been demonstrated by tilting of the HN22 sheet with respect to the incident beam. The material's availability, relatively large aperture, large field of view, and low cost make it an excellent candidate for use as an infrared retarder for systems operating in this wave band. Thus HN22 may be employed as an inexpensive half-wave linear retarder and used for rotating the plane of polarization as well as for conversion between circular polarization states. © 1997 Optical Society of America

Key words: Polarization, Mueller matrix, polarizer, birefringence, retardance, infrared.

1. Introduction

Dichroic sheet polarizers are well known and typically employed for their high extinction ratios, low scattering coefficients, large available apertures, relatively broad fields of view, and extremely low cost.^{1–4} Of particular interest is Polaroid HN22 molecular sheet polarizer, the most popular sheet linear polarizer. HN22 exhibits a contrast ratio of as high as 10^5 (extinction value of $\approx 0.0009\%$) across most of the visible spectrum.^{5–7} The overall transmittance of this material decreases in the near infrared and reaches a minimum near 2.9–3.0 μm . This absorption is due to a vibrational–rotational mode of the OH⁻ radical in the polyvinyl alcohol matrix.^{8,9} HN22 has a transmission window between 3.6 and 5.4 μm where the transmittance is high enough ($\approx 20\%$) to use the HN22 as an optical element. As is shown below, HN22 is no longer a strong polarizer in this region but does have significant retardance. The retardance exhibited by HN22 results from birefringence, arising from two sources. Molecular polarizers such as HN22 are formed by unidirectionally stretching the polymer polyvinyl alcohol and impregnating the material with iodine molecules. The anisotropic structure resulting from the stretching causes an underlying birefringence in the polyvinyl

alcohol and has been called accidental birefringence.⁹ The iodine molecules bond to the matrix in a preferred orientation to form polyiodine chains that are themselves anisotropic and hence birefringent, thereby contributing to what is referred to as intrinsic birefringence.^{9,10} These two types of birefringence have axes that are not only aligned with each other but are parallel to the dichroic axes of the sheet polarizer. The HN22 polarizer is known to exhibit an overall positive axial birefringence in the visible and to have an optical axis that is perpendicular to the material's transmission direction. Hence the transmission direction for the sample is also the direction of its fast axis, since the fast axis is perpendicular to the optical axis for a positive, uniaxial material.

2. Mueller Matrix Spectrum

A characterization of the infrared polarization properties of HN22 was undertaken with the infrared spectropolarimeter at the University of Alabama in Huntsville (Fig. 1).^{11–13} This Fourier transform infrared spectropolarimeter measures the Mueller matrix spectrum of a sample, thereby determining the polarization characteristics including linear and circular diattenuation and linear and circular retardance of a sample.¹⁴ The University of Alabama in Huntsville (UAH) Fourier Transform Infrared Spectropolarimeter is described in Section 4, and the normalized Mueller matrix spectra presented here are defined in Appendix A.

Figure 2 shows the normalized Mueller matrix spectrum measured for the HN22 polarizer at normal incidence across the 3.5–5.5- μm waveband. The HN22 sample is oriented with the polarizer's transmission axis horizontal. The m_{00} element spectrum in the

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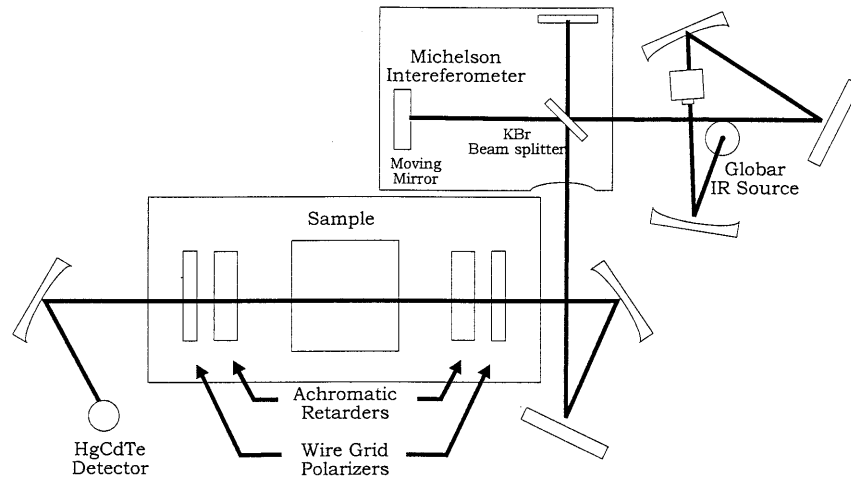


Fig. 1. Infrared spectropolarimeter. Radiation from the source is collimated before introduction into the Michelson interferometer. A dual-rotating retarder polarimeter employing two polarizers and two achromatic retarders is incorporated into the sample chamber of the Fourier transform infrared spectrometer. The transmitted signal is acquired with a HgCdTe detector.

upper left corner contains the transmission spectrum for HN22 when unpolarized light is incident. This transmission spectrum has been enlarged in Fig. 3. The highest transmission (>24%) occurs between 4 and 4.6 μm , with additional peaks at 5.1 and 5.3 μm and absorption bands at 3.6, 4.25, 5.15, and 5.5 μm .

Figure 2 contains spectra of each of the 16 elements of the normalized Mueller matrix. The spectra of many of the elements are nearly zero, including m_{01} , m_{02} , m_{03} , m_{10} , m_{12} , m_{01} , m_{13} , m_{20} , m_{21} , m_{30} , and m_{31} . The spectrum of m_{11} is nearly 1. Only elements m_{22} ,

m_{23} , m_{32} , and m_{33} are significantly different from 0 or 1; these are the Mueller matrix elements associated with a linear retarder oriented with a horizontal or vertical fast axis. In the visible, the normalized Mueller matrix of HN22 is approximately

$$\frac{1}{2} \begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \quad (1)$$

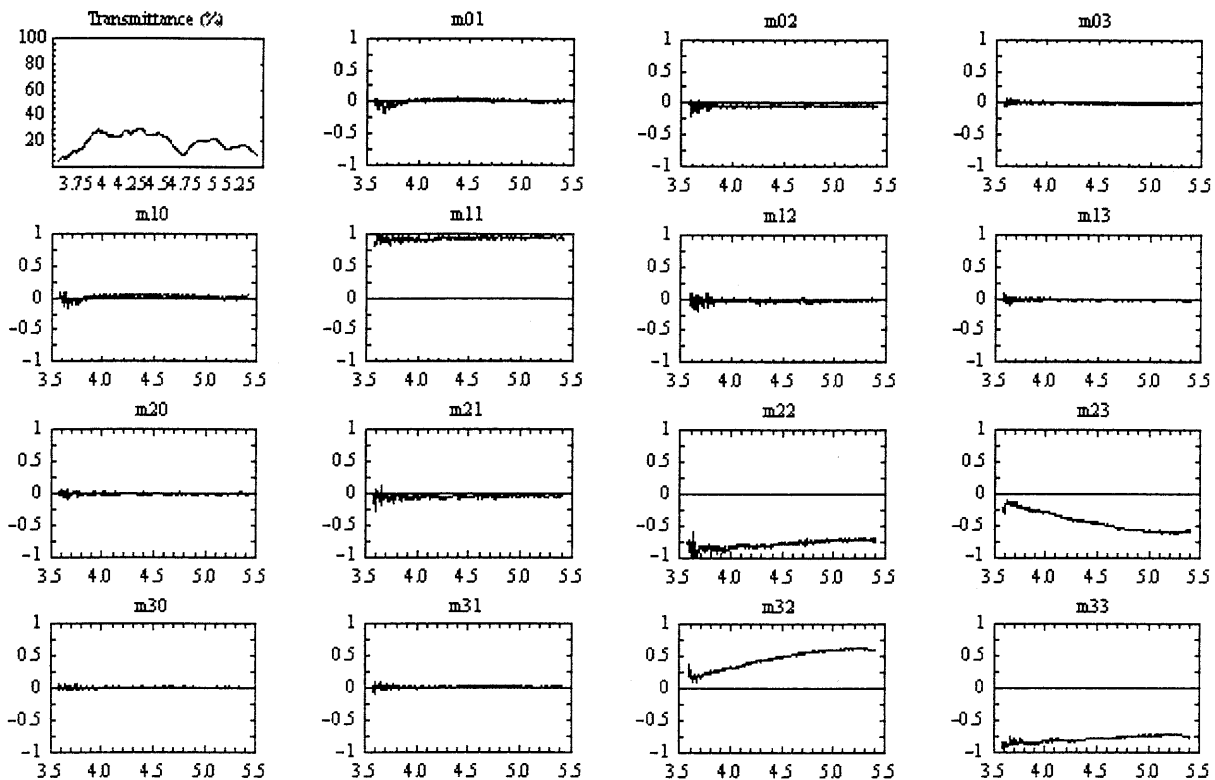


Fig. 2. Normalized Mueller matrix spectrum of Polaroid HN22 consists of 16 Mueller matrix element spectra. The nonzero m_{22} , m_{23} , m_{32} , and m_{33} elements indicate a linear retarder.

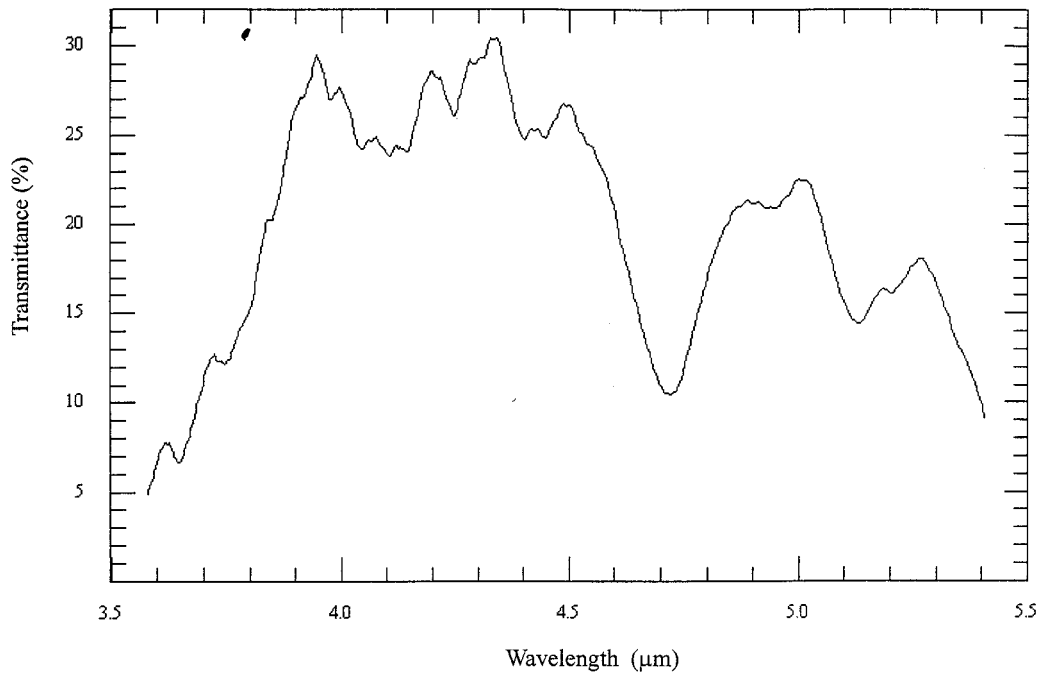


Fig. 3. Transmittance of HN22 from 3.6 to 5.4 μm for unpolarized light at normal incidence.

the Mueller matrix of a horizontal linear polarizer. Since the matrix spectrum of Fig. 2 does not resemble Eq. (1), HN22 clearly is not a horizontal linear polarizer in the 3.5–5.5- μm band. On examination of Fig. 2, particularly near 3.5 μm , the matrices seem to be similar to the Mueller matrix for a half-wave linear retarder with a horizontal fast axis, HWLR(0°):

$$\text{HWLR}(0^\circ) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}. \quad (2)$$

At all wavelengths the Mueller matrix spectrum resembles the Mueller matrix for a linear retarder LR(θ , δ) of arbitrary retardance δ oriented with its fast axis at 0° ,

$$\text{LR}(0^\circ, \delta) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos(\delta) & \sin(\delta) \\ 0 & 0 & -\sin(\delta) & \cos(\delta) \end{bmatrix}, \quad (3)$$

as will be confirmed by the Mueller matrix decomposition analysis in the Section 3.

In the regions of low (i.e., $<7\%$) transmittance, the signal-to-noise ratio of the spectropolarimeter is small, and the data are less reliable. This is particularly evident in the noise of the Mueller matrix spectra in the region below 3.7 μm , in a thin band near 4.7 μm , and above 5.4 μm . Accordingly, the most accurate data lie between 3.7 and 5.4 μm except for a small absorption band between 4.65 and 4.8 μm .

3. Diattenuation and Retardance Spectra

The diattenuation spectrum and the retardance spectrum have been calculated from the Mueller matrix spectrum by use of the Mueller matrix decomposition algorithms of Lu and Chipman.¹⁵ Figure 4 shows the magnitude of the diattenuation as a function of wavelength. When the diattenuation is zero, all incident polarization states have the same transmission; for a diattenuation of one, the element in an ideal polarizer.¹⁵ The infrared diattenuation of HN22 averages $\sim 6\%$, so HN22 is a very weak polarizer across this spectral band. For comparison, the visible diattenuation is nearly one, as is true of all good polarizers. This small diattenuation in the infrared region should be considered when the HN22 is used for precision work, as this diattenuation is not so small that it can always be ignored. Neglecting this effect would lead to measurement accuracy errors that may become non-negligible. Knowing this diattenuation, however, allows for compensation of the error it may introduce. For example, because of this 6% diattenuation, if one is seeking to generate circularly polarized light from linearly polarized light, then instead of placing an ideal quarter-wave retarder with its axis at 45° , an 88.3° retarder with 6% diattenuation should be inserted with its axis at 45° . The ability to vary the retardance of HN22 to 88.3° would allow the material to function as an ideal, inexpensive quarter-wave plate with minimal errors introduced by its nonzero diattenuation. This variability is in fact realized by tilt tuning the sample and is discussed below.

Figure 5 shows the measured retardance magnitude for a normally incident beam onto a sample of HN22 oriented with its transmission axis horizontal.

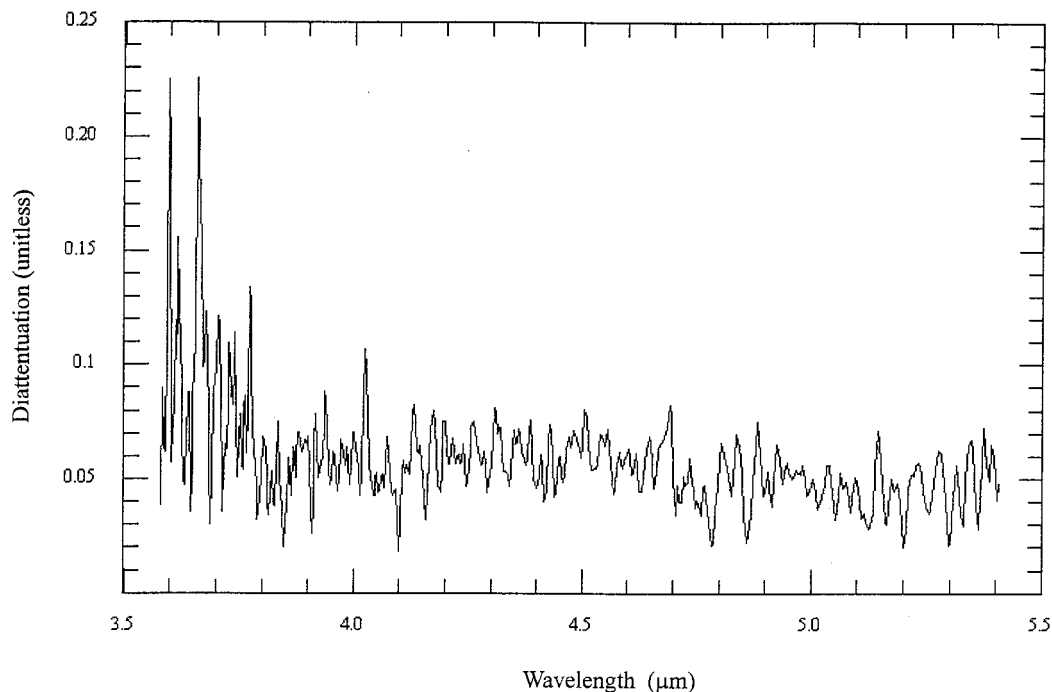


Fig. 4. Diattenuation spectrum of HN22 is small, $\sim 6\%$. When the diattenuation is zero, all incident polarization states have equal transmittance. Thus the sheet polarizer is a weak polarizer but a good retarder in the infrared.

The retardance magnitude is slightly less than 180° for the short-wavelength end of the spectrum and slowly decreases as the incident wavelength increases. Therefore HN22 performance approaches that of a half-wave plate at $3.6 \mu\text{m}$.

It is well known that the retardance of a retardation plate may be tuned by simply tilting the plate

with respect to the incident beam.¹⁶⁻¹⁹ We have demonstrated this angle tuning for HN22 with a sequence of spectropolarimeter measurements in which the HN22 was rotated in 10° increments about the polarizer's extinction axis. Figure 6 shows eight retardance spectra acquired as the HN22 rotates about the transmission axis in the visible, the fast axis of

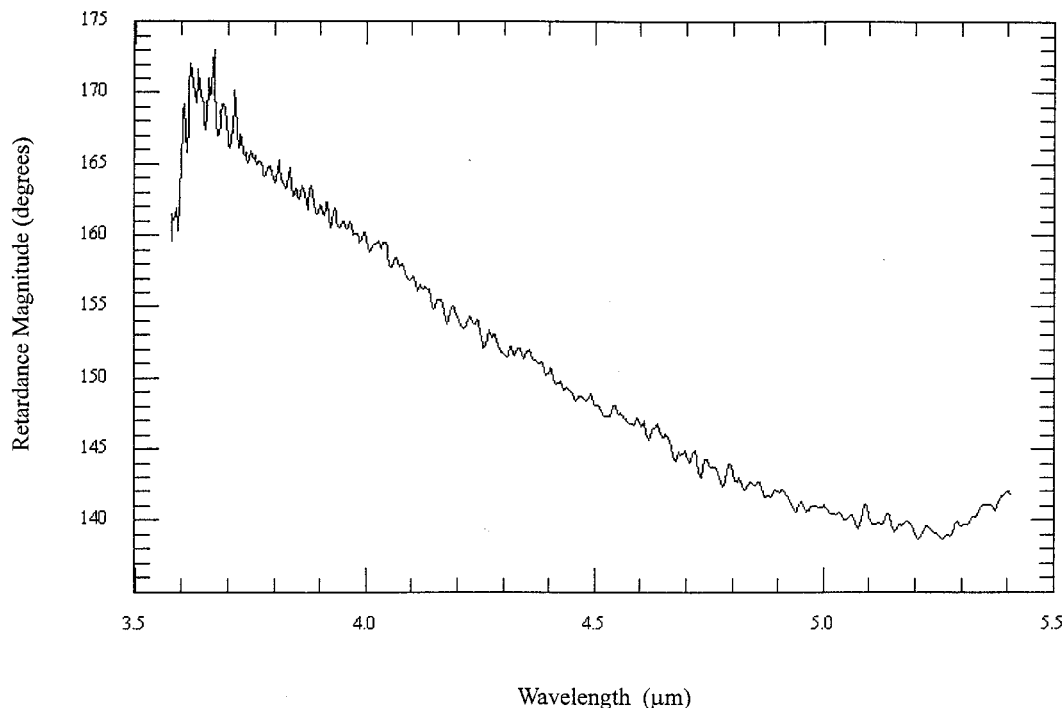


Fig. 5. Retardance spectrum of HN22 at normal incidence varies from 140° to 170° making it nearly a half-wave linear retarder.

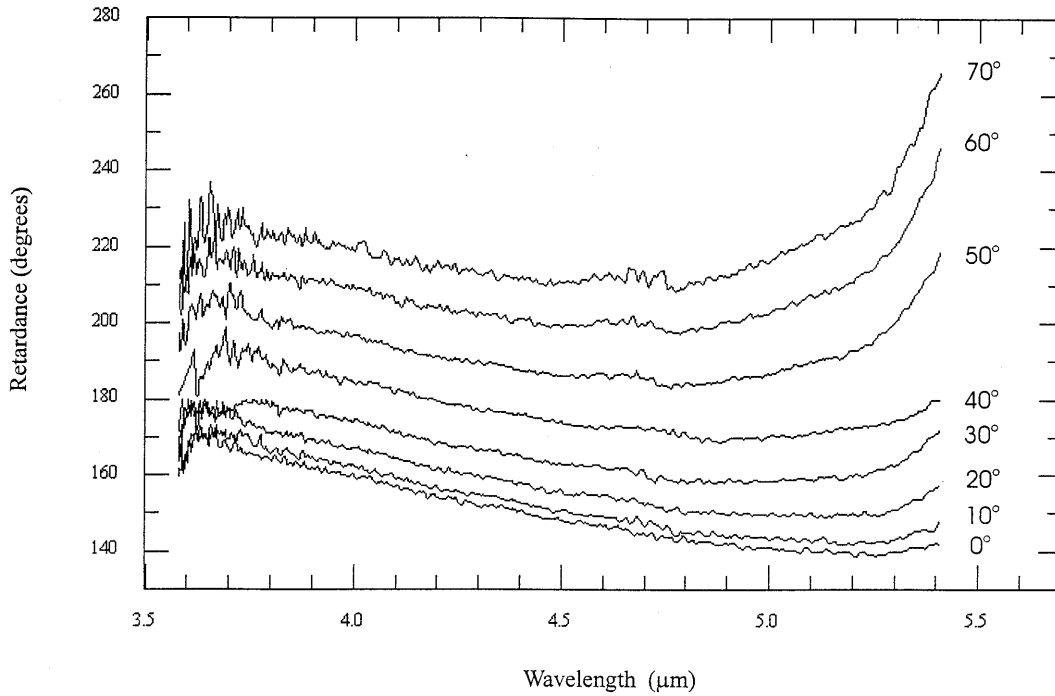


Fig. 6. Retardance spectra as the sample is rotated about its transmission axis displays an increasing retardance. Thus the retardance is readily tuned to a half-wave.

the retarder. The retardance steadily increases with angle of incidence. This is potentially useful for tuning the HN22 to a half-wave of retardance for any wavelength in the measured band. For our sample a half-wave of retardance was attained at $\sim 30^\circ$ for $3.8 \mu\text{m}$, 40° for $4.5 \mu\text{m}$, and 40° for $5.4 \mu\text{m}$. In Fig. 7 the HN22 was rotated about the extinction

axis of the visible polarizer, and the retardance was reduced. At large enough angles of incidence a quarter-wave of retardance was attained for wavelengths greater than $4.75 \mu\text{m}$. Figure 8 shows the variation of retardance with angle of incidence at $4.5 \mu\text{m}$. These curves are approximately quadratic for angles of incidence below $\approx 30^\circ$ as expected.¹⁶⁻¹⁸

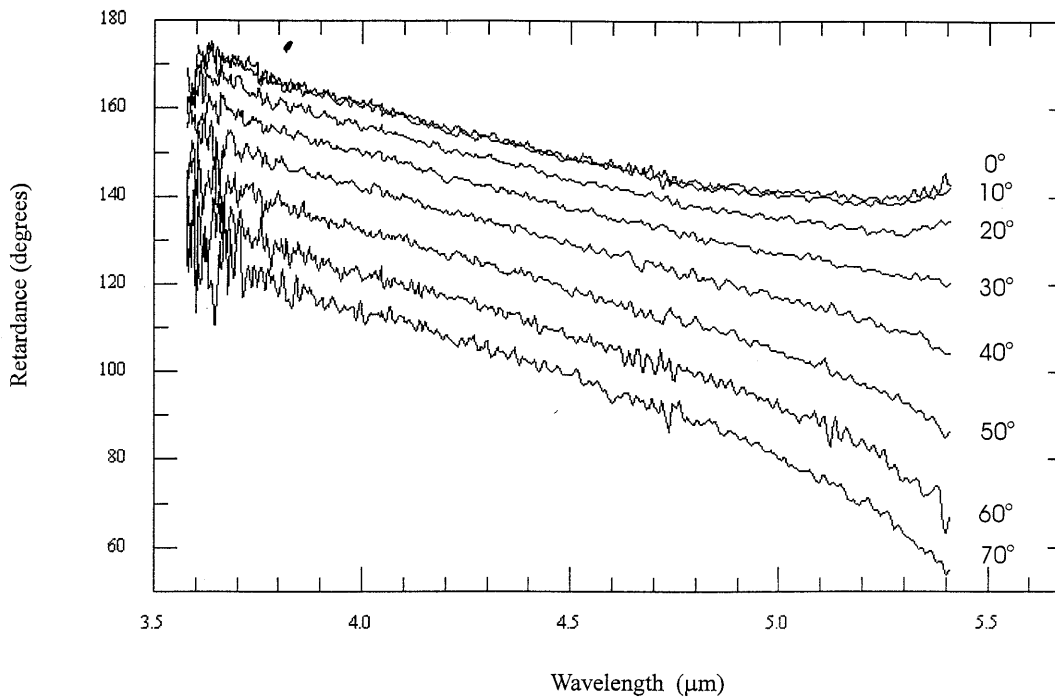


Fig. 7. Retardance spectra as the sample is rotated about the extinction axis displays a decreasing retardance.

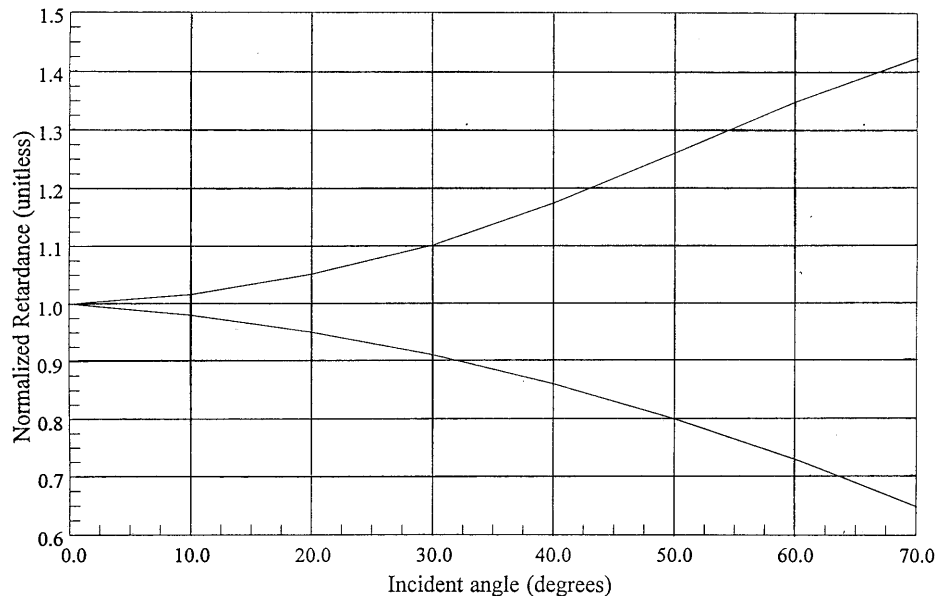


Fig. 8. Normalized retardance as a function of incident angle for 4.5 μm is approximately quadratic. The upper curve is for rotation about the polarizer's transmission axis, and the lower curve is for rotation about the extinction axis. Wavelength, 4.5 μm .

The functional dependence of the retardance on the ray angle within the material is sometimes presented in the literature and has a cosine dependence. The exact equations relating these two parameters for both the case where the optical axis is horizontal and the vertical case may be found in Ref. 19.

4. University of Alabama in Huntsville Fourier Transform Infrared Spectropolarimeter

These measurements were performed with the UAH Fourier-transform infrared spectropolarimeter, a modified spectrometer that is capable of measuring the Mueller matrix spectrum of a sample. A dual-rotating retarder Mueller polarimeter is incorporated into the sample compartment of a Fourier transform infrared spectrometer. By illuminating the sample with a sequence of known polarization states and analyzing the transmitted states, we can determine the Mueller matrix.¹³ The sequence of states is generated in the spectropolarimeter by rotating the first quarter-wave plate in 6° increments and the second in 30° increments between spectra. This overdetermines the 16 measurements necessary for a Mueller matrix; the redundancy reduces the effect of noise on the measurement. All equipment automation and data acquisition are performed with a Nicolet 6000 Fourier transform infrared microcomputer, and data reduction routines are carried out on an IBM compatible personal computer.

5. Conclusion

The popular sheet polarizer HN22 is a retarder in the 3.6–5.4- μm transmission band, where it functions approximately as a half-wave plate. Mueller matrix measurements over a range of incident angles verified that the HN22 is tunable to exactly one half-wave of retardance for any given wavelength within the

3.6–5.4- μm band. Angle of incidence tuning to a quarter-wave of retardance has been demonstrated for 4.9–5.4 μm . Diattenuation measurements indicate that HN22 is a very weak polarizer in the infrared.

Appendix A: Normalized Mueller Matrix

In this paper, Mueller matrix spectra are presented in the form of normalized Mueller matrices to show the polarization properties most clearly without the superposition of the transmission spectrum. The normalized Mueller matrix \mathbf{m} is related to the Mueller matrix elements M_{ij} by

$$\mathbf{m} = \begin{bmatrix} M_{00} & M_{01}/M_{00} & M_{02}/M_{00} & M_{03}/M_{00} \\ M_{10}/M_{00} & M_{11}/M_{00} & M_{12}/M_{00} & M_{13}/M_{00} \\ M_{20}/M_{00} & M_{21}/M_{00} & M_{22}/M_{00} & M_{23}/M_{00} \\ M_{30}/M_{00} & M_{31}/M_{00} & M_{32}/M_{00} & M_{33}/M_{00} \end{bmatrix}. \quad (\text{A1})$$

In a normalized Mueller matrix, all elements M_{ij} except M_{00} are divided by M_{00} , so

$$m_{ij} = \frac{M_{ij}}{M_{00}}, \quad (i, j) \neq (0, 0). \quad (\text{A2})$$

Normalized Mueller matrix elements are represented with lower case m , and unnormalized Mueller matrix elements are capitalized. Normalized Mueller matrix elements are restricted to the range $-1 \leq m_{ij} \leq 1$. Normalized Mueller matrices are superior for representing the polarization characteristics associated with a Mueller matrix spectrum. If a Mueller matrix spectrum is not normalized, all other matrix element spectra have the M_{00} spectrum superposed (multiplied) on their polarization information. M_{00} is not normalized, as it is the transmission spectrum

of the sample for unpolarized illumination, which is commonly measured with spectrophotometers.

References

1. E. H. Land, "Some aspects of the development of sheet polarizers," *J. Opt. Soc. Am.* **41**, 957–963 (1951).
2. E. H. Land and C. D. West, "Dichroism and dichroic polarizers," *Colloid. Chem.* **6**, 160–190 (1946).
3. E. Collett, *Polarized Light Fundamentals and Applications* (Marcel Dekker, New York, 1992), Chap. 5, pp. 67–90; Chap. 23, pp. 468–479.
4. R. P. Blake, A. S. Makas, and C. D. West, "Molecular-type dichroic film polarizers for 0.75 to 2.5 μ -radiations," *J. Opt. Soc. Am.* (abstract) **39**, 1054 (1949).
5. W. A. Shurcliff, *Polarized Light* (Harvard U., Cambridge, Mass., 1962), Chap. 4, pp. 43–64.
6. Polaroid Corporation, 1 Upland Rd. N2, Norwood, Mass. 02062.
7. J. L. Pezzaniti and R. A. Chipman, "Linear polarization uniformity measurements taken with an imaging polarimeter," *Opt. Eng.* **34**, 1558–1567 (1995).
8. G. Trapani, Polaroid Corporation, Commercial Optics Division, Nor-1 Mezzanine, 1 Upland Rd., Norwood, Mass. 02062 (personal communication).
9. S. Krimm, C. Y. Liang, and G. B. B. M. Sutherland, "Infrared spectra of high polymers. V. Polyvinyl alcohol," *J. Polym. Sci.* **22**, 227–247 (1956).
10. V. K. D. Mielenz and R. C. Jones, "Die Eignung von Polarisationsfiltern für photometrische Messungen," *Optik* **15**, 656–669 (1957).
11. D. B. Chenault and R. A. Chipman, "Measurements of linear diattenuation and linear retardance spectra with a rotating sample spectropolarimeter," *Appl. Opt.* **32**, 3513–3519 (1993).
12. D. H. Goldstein, "Mueller matrix dual-rotating retarder polarimeter," *Appl. Opt.* **31**, 6676–6683 (1992).
13. D. H. Goldstein, R. A. Chipman, and D. B. Chenault, "Infrared spectropolarimetry," *Opt. Eng.* **28**, 120–125 (1989).
14. R. A. Chipman, "Polarimetry," in *Handbook of Optics*, M. Bass, ed. (McGraw-Hill, New York, 1993), pp. 22.1–22.33.
15. S.-Y. Lu and R. A. Chipman, "Interpretation of Mueller matrices based on polar decomposition," *J. Opt. Soc. Am. A* **13**, 1106–1113 (1996).
16. S. McClain, "Birefringent polarization ray tracing: theory and applications," Ph.D. dissertation (University of Alabama in Huntsville, Huntsville, Ala., 1992), Chap. 6.
17. J. Bennet, "Polarizers" in *Handbook of Optics*, M. Bass, ed. (McGraw-Hill, New York, 1993), pp. 22.1–22.33.
18. A. M. Title and W. J. Rosenberg, "Tunable birefringent filters," *Opt. Eng.* **20**, 815–823 (1981).
19. P. D. Hale and G. W. Day, "Stability of birefringent linear retarders (waveplates)," *Appl. Opt.* **27**, 5146–5153 (1988).