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PRESENT STATUS OF AUTOMATIC ELLIPSOMETERS

Rolf H. Muller

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PRESENT STATUS OF AUTOMATIC ELLIPSOMETERS

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ABSTRACT

Operating principles and capabilities of presently-built automatic ellipsometers are reviewed. The instruments are classified according to their optical principles of operation and their capabilities are compared on the basis of uniform performance criteria. Possible future developments are indicated.

The principal purpose of automatic ellipsometers that have been built in the last few years is to overcome the slow response associated with manual operation. In most cases, increased resolution has also been achieved and many automatic ellipsometers are suited for on-line data evaluation. Transient phenomena on surfaces have thus become amenable to ellipsometric observation. Another use of automatic ellipsometers lies in the emerging technique of spectroscopic ellipsometry, most forms of which require fast response to be practically viable.

Poincaré Sphere

The operation of many ellipsometer arrangements (supposing ideal components) is most conveniently illustrated by use of the Poincaré sphere. The same procedures employed previously for following the state of polarization through the components of an ellipsometer¹ will be used here. The coordinate grid that represents the geometrical parameters of elliptic polarization is shown in Fig. 1a. An elliptic polarization E is characterized by the azimuth θ of the major ellipse axis (measured from the plane of incidence H) and the axial ratio² $\tan\gamma$ (positive for left-hand rotation). The "equator" of the sphere is also used to indicate the azimuth of optical components. The physical parameters of elliptic polarization are represented by the coordinate grid in Fig. 1b. They are the relative phase Δ and the relative amplitude parameter ψ .

The effect of a retardation plate (compensator) is shown in Fig. 1c (which is similar to Fig. 1b), with F representing the azimuth of the fast axis of the retardation plate. A polarization state B is transformed into state D by the phase change δC of the retardation plate. Note that all angles except phase angles appear doubled on the sphere. The amplitude (or square root of irradiance) of an elliptic

polarization transmitted by an analyzer can be represented by the length of the chord between point E, which represents the elliptic polarization, and point A' which represents the absorption direction of the analyzer A (Fig. 1d). A small circle I around A' represents the locus of polarization states of equal transmitted irradiance (intensity).

Classification of Automatic Ellipsometers

Automatic ellipsometers can be classified according to different criteria that may involve suitability for certain applications, ease of data collection, on-line data processing, spectral scanning or use of special components and electronic circuitry. For the present purposes, I will use optical criteria for the classification summarized in Tables I and II. The principal question is whether or not compensation of the elliptic polarization (and extinction) is achieved. Sub-groups consider the modulation employed and the kind of irradiance information obtained in the non-compensating case or the means by which control signals are derived from the modulation, and compensation is achieved in the compensating case. The sequence of optical components listed in Tables I and II follows the propagation of light and does not include light source and photodetector.

Non-Compensating Ellipsometers

Non-compensating automatic ellipsometers provide irradiance measurements, from which parameters of elliptic polarization can be derived. Some non-compensating instruments can determine reflectance or changes in reflectance as an additional measured quantity.

Off-null irradiance measurements are the oldest attempt to decrease the response time of ellipsometers. This mode of operation may not be

considered "automatic" in the strict sense, but is included here because it serves some of the same purposes. Starting from complete compensation⁴ (e.g., for a bare surface), an increase in transmitted irradiance, as surface properties change, is generally due to changes in both ψ and Δ . The increase in irradiance is non-linear and not sensitive to very small changes in ψ or Δ because of a sine-square dependence on the change. By deliberately setting some ellipsometer components off compensation at the start, however,⁵ the change in transmitted irradiance can be made to show a linear response, be more sensitive to small changes in the state of polarization, and to primarily represent changes in ψ or Δ (provided that these changes are small, e.g., $1-3^\circ$).

There are many possible ways by which the desirable off-compensation conditions can be achieved. Figure 2 illustrates such a possibility for the case of elliptic polarization incident on the specimen and use of a quarter-wave compensator. In Fig. 2a, an elliptic polarization state E, that differs from the restored linear polarization A' obtained at compensation, is generated by an offset of the polarizer. It can be seen that the transmitted amplitude, represented by the length of the chord A'E, is primarily sensitive to changes in Δ . On the other hand, an offset in the analyzer azimuth, illustrated in Fig. 2b, results in an irradiance response primarily sensitive to changes in ψ . If the transmitted irradiance is affected by changes in reflectivity in addition to changes in the state of polarization, the interpretation is more complex.

Rotating-analyzer ellipsometers⁶⁻²¹ produce a transmitted irradiance that varies as a function of the azimuth of the rotating component.

Figure 3 shows on the Poincaré sphere an elliptic polarization state E

that may have resulted from the reflection of linear polarization. A full rotation of the analyzer corresponds to two rotations of A and A' (indicated by the double-arrow) around the equator of the Poincaré sphere. If A'E represents the minimum transmitted amplitude, the azimuth a' of A' is the azimuth θ of the major ellipse axis. The ratio of the minimum and maximum amplitudes (or square roots of the measured irradiances) is the axial ratio $\tan \gamma$ of the ellipse. The geometrical parameters of elliptic polarization can thus be directly measured. Instead of measuring the minimum and maximum transmitted irradiances with the associated analyzer azimuths,^{7,8} irradiance measurements can also be made at fixed azimuth intervals.^{6,9-14} A sinusoidal function is then fitted to the measured points by Fourier-analysis¹⁰⁻¹⁴ and the desired irradiances and azimuths are derived from the function.

Rotating-analyzer instruments in their simplest form employ a polarizer of 45° azimuth and use no compensator.^{6-9,11,12} Thus, incident p and s-components are in phase and of equal amplitude. Certain states of polarization (or ranges of film thickness) can be determined more accurately with polarizer azimuths other than 45° and by the addition of a compensator.^{7,8,11,13} The derivation of ellipsometer parameters from the measurements is then a bit more involved. Again, phase-sensitive detection or Fourier-analysis techniques can be used for measurement.

The state of polarization can also be determined by scanning only an angular segment of the ellipse with an oscillating analyzer.¹⁵ Precision and accuracy of rotating-analyzer ellipsometers have been extensively investigated.¹⁶⁻¹⁸

The use of a rotating polarizer (or analyzer) between a fixed polarizer and analyzer¹⁹⁻²¹ results in a double-modulation of the

transmitted irradiance and allows one to replace the irradiance ratio measurement by another azimuth (phase) measurement.

Periodic variations in transmitted irradiance from which ellipsometer parameters can be derived have also been generated with a compensator of variable retardation. Such retardation (polarization) modulation has been achieved with a photoelastic device.²²⁻²⁴ As illustrated in Fig. 4, the transmitted amplitude $A'R$ is a complex function of the retardation modulation dM . An error analysis of the technique is also available.²⁵ A differential ellipsometer²⁶ in which two different specimens are compared, is a special variation of the phase modulation technique.

Compensating Ellipsometers

The operation of compensating automatic ellipsometers requires an error signal to control a servo mechanism that drives two variable components to compensation. This signal is derived, normally by phase-sensitive detection of the response, from a modulation of the state of polarization.²⁷ Compensation is accomplished by the control of azimuths or retardations.

With elliptic polarization incident on the specimen and use of a quarter-wave compensator, the state of polarization through the instrument is indicated in Fig. 5a. The linear polarization P , due to the polarizer, is transformed into the incident elliptic polarization E by the action of the quarter-wave plate with fast axis Q and retardation δQ . The change in polarization due to reflection, as before,¹ is shown as a change Δ in relative phase and a change (ψ) in relative amplitude parameter, resulting in the restored linear polarization A' . Error signals have been derived by mechanical²⁸⁻³⁰ or magneto-optical^{31,32} modulation of polarizer and analyzer azimuth. Stepwise azimuth changes have been

obtained by the use of rotating, optically active half-disks.³³ The optimum depth of azimuth modulation has been investigated.³⁴

Figure 5a illustrates (for zone A-1¹) how a modulation dp of the polarizer azimuth causes a modulation of the compensated linear polarization by $d\Delta$ and results in a proportional variation of transmitted amplitude. Similarly, the modulation da in analyzer azimuth produces a deviation $d\psi$ from the compensated linear polarization (Fig. 5b). It can be seen that the two modulations are orthogonal to each other, a necessary condition (in addition to separating control channels by phase or frequency) to avoid cross-talk between control channels. Compensation has been achieved by electro-mechanical control of polarizer and analyzer azimuths²⁸⁻³⁰ or by magneto-optical (Faraday cell) rotation of the plane of polarization, with polarizer and analyzer of fixed azimuths.^{31,32}

A modulation of the state of polarization can also be accomplished with retardation plates of electrically variable retardation (e.g., photo-elastic or electro-optic cells).^{22-24,35-39} Figure 6 shows an azimuth vibrator "of the Sénarmont type"³⁷ in which a retardation modulator of fixed azimuth (fast axis M, retardation dM), in combination with a quarter wave plate ($Q, \delta Q$), has the same effect as the modulation of the polarizer azimuth, dp . The effect of two retardation modulators M1 and M2 of variable azimuth, coupled to analyzer and polarizer³⁸ is illustrated in Fig. 7. Compensation has been accomplished by electro-mechanical rotation of polarizer and analyzer.

Two compensators of variable retardation have been used for modulation and compensation, with polarizer, quarter-wave plate and analyzer of fixed azimuths.³⁹ The two compensators produce restored circular polarization L (Fig. 8) which is subsequently converted to linear polarization A' by

the quarter-wave plate Q and extinguished by the analyzer A. The two modulations d1 and d2 have been operated with 90° phase difference between them. In practice, the sequence of components shown in Table II and Fig. 8 can also be reversed.

In contrast to the usual compensation to linear polarization, followed by extinction, compensation to circular polarization has also been reported.⁴⁰

Error signals derived from modulations of the state of polarization can also be used for fast or precise manual nulling.^{33,41-43,45,46} This approach to decreasing the response time of ellipsometers deserves further attention, particularly in combination with the use of digital angle - position encoders^{12,30} and printers.

The modulation in the state of polarization of light employed both in compensating and non-compensating ellipsometers must be separated from the modulation of the properties of the specimen surface ("modulation ellipsometry") that has been employed.⁴⁷⁻⁴⁹

Performance Criteria

In order to compare the performance of different automatic ellipsometers, I propose to consider performance criteria that are closely related to the practical use of the instruments and can be quantitatively measured. Among them are the following criteria that pertain to the ability of observing transient surface phenomena:

1. Slew rate. The maximum rate of change that can be followed within specified limits of accuracy.
2. Resolution. The smallest change that can be detected (precision).
3. Dynamic range. The maximum range of change that can be followed.
4. Accuracy. Comparison of static and dynamic measurements, systematic absolute errors.

We have introduced the determination of these quantities with surfaces of rapidly varying properties.⁵⁰ Other criteria that enter into a comparison of automatic ellipsometers are related to specific applications and modes of operation. Two of them are:

5. Adaptability to wavelength scan.
6. Suitability (or need) for use of an on-line computer.

Since most instrument designs allow one to trade high performance in one characteristic for another (e.g., resolution vs speed) the specification of equipment capabilities should include the interrelation between characteristics.

Comparison of Performance

An attempt to compare performance characteristics of some instruments is shown in Tables III and IV. Because the documentation of the capabilities of most automatic ellipsometers reported in the literature is quite incomplete, some of the data had to be estimated. Since rotating-analyzer instruments primarily measure the geometrical parameters of elliptic polarization, θ and γ , these quantities are given in the table. Under many circumstances the increment in the physical parameter Δ is about twice that of γ , while changes in ψ are about equal to those in θ .

The highest slew rate appears to have been accomplished with rotating-analyzer instruments. The figures shown are based on a single rotation. Averaging over several rotations is undoubtedly required to achieve most of the resolution figures quoted, so that practical slew rates will be at least an order of magnitude lower. The time-constant of the control circuit on which the slew-rates of compensating instruments has been based, provides, however, for a reduction in noise. Another reason why

the slew-rates listed for rotating-analyzer and compensating ellipsometers cannot be directly compared results from the fact that rotating-analyzer instruments provide the first measurement of even a small change in the state of polarization (disregarding considerations of noise-reduction) only after the time required for half a rotation. An error signal in a compensating instrument, by the same token, is in principle available after one cycle of the (much higher) modulating frequency. Thus, the fastest rotating-polarizer ellipsometer²⁰ listed in Table III provides measurements at 10 ms intervals, while the fastest compensating ellipsometer³² of Table IV could provide an error signal every 0.1 ms. Even with noise-averaging and compensation delays, the latter instrument can record a 1.6° azimuth change after 1 ms. The compensating ellipsometer can, therefore, be superior to the rotating polarizer instrument for observing fast but relatively small changes (e.g., less than 16° of ψ in less than 10 ms). The highest frequencies are employed with retardation modulation. The potential for achieving correspondingly high slew rates has, however, not been realized yet for this technique.

The best resolution obtained with compensating and non-compensating instruments is about the same, of the order of 10^{-3} deg in Δ . The fact that resolution is of similar magnitude for both classes of instruments agrees with theoretically-established resolution limits under shot-noise limited conditions,⁵¹ although such conditions are more easily reached with non-compensating instruments. The resolution of non-compensating ellipsometers can depend strongly on the state of polarization (optical constants of the reflecting surface),^{9,11,16,19} while for compensating instruments, it is almost independent of them.⁵² A theoretical resolution

limit of 10^{-5} deg in Δ may someday be accomplished under the most favorable circumstances.⁵¹ The mechanical azimuth modulation²⁹ is not a true modulation (the minimum is traversed only once), but rather like a rapid manual measurement for which a practical resolution limit of 10^{-2} deg can be expected.⁵¹

The dynamic range of rotating analyzer ellipsometers is basically not restricted, except that the sense of rotation of the ellipse cannot be determined. Thus, the sign of γ (range 0-45°) or Δ (range 0-180°) cannot be determined. Similarly, data derived from retardation modulation do not allow one to distinguish $\tan\psi$ from $\cot\psi$.⁵² The dynamic range of compensating instruments is normally limited by the operating range of variable components rather than ambiguities in interpretation. Only the first and the last instrument listed in Table IV are able to measure all possible states of polarization without manual adjustments.

The accuracy of most non-compensating ellipsometers that employ irradiance measurements is primarily limited by the requirements for linear, polarization-independent response of the photodetector and constant emittance of the light source. Compensating instruments are inherently insensitive to these parameters and can be expected to provide higher accuracy than non-compensating ones.^{51,52} An experimental characterization of accuracy should at least compare dynamic with static measurements of the same specimen.⁵⁰ An analysis of absolute accuracy, that would include all systematic errors^{11,17,18,22,24,25} is much more difficult and can, at present, hardly be verified experimentally. Insufficient data on accuracy are available to permit a comparison between instruments.

Rotating analyzer ellipsometers are most easily adapted for wavelength scanning as long as they are operated without a compensator, because most polarizing elements operate over a range of wavelengths. Since most compensating plates change their retardation with wavelength, compensating ellipsometers are less suited for wavelength scan, although the dispersion in retardation could be accounted for with a dedicated computer. The use of achromatic quarter-wave plates, such as those derived from the Fresnel rhomb^{53,54} would, however, appear more desirable. The spectral transmission of materials for magneto-optical or electro-optical components will also have to be considered in comparing the suitability of different designs for wavelength scanning.

The need for an on-line computer for Fourier analysis has been indicated in Tables I and III. In addition, a computer has long been used in an electro-mechanical compensating instrument.²⁹ Computers are particularly desirable where the ellipsometer parameters are not simply related to the measured quantities.

No single best automatic-ellipsometer design can at present be identified. While the fastest response is obtained with a non-compensating type, a compensating instrument would be chosen for best accuracy.

Outlook

The primary purpose of present developments in automatic ellipsometry is probably to establish spectroscopic ellipsometry as a new, powerful investigative tool. The range of wavelengths is likely to reach from the near u.v. to the near i.r. Efforts will certainly be directed towards achieving much shorter response times for the measurement of

fast chemical and physical processes at surfaces. The microsecond range seems a realistic target. The inherent noise-limitations for resolution will be approached more closely, particularly with slow operation. The utility of very high resolution measurements, e.g., 10^{-5} deg, although desirable for spectroscopic purposes,¹³ is at present limited by uncertainties in physical interpretation. For the production control use of ellipsometers, recent progress toward simplifying operation and data evaluation¹¹ can be expected to continue. Further decreases in the cost of small computers will make the use of many ellipsometer designs attractive that have not yet been realized because the data are not obtained in a readily interpretable form. A rotating compensator would be such an example. It would seem that most of the modulation schemes employed in non-compensating ellipsometers could also be used in compensating ellipsometers, particularly if compensation is not restricted to restored linear polarization and extinction but also includes restoration to circular or specified elliptic polarization-states. On-line computers could also optimize operating conditions where these depend on the properties of the reflecting surface. The application of compensators with electrically variable and measurable retardation could result in the realization of several so far unused ellipsometer arrangements that promise to combine speed and resolution. Also, such compensators could be programmed to remain quarter-wave during a wavelength-scan. In all, substantial developments can be expected in the near future in the construction and use of automatic ellipsometers.

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List of Symbols

A	analyzer transmission axis; analyzer
A _{rot}	rotating analyzer
A'	analyzer absorption axis; restored linear polarization
a	azimuth of analyzer transmission axis
a'	azimuth of analyzer absorption axis
C	fast axis of variable compensator; variable compensator
da	azimuth modulation amplitude of analyzer
dp	azimuth modulation amplitude of polarizer
dM	retardation modulation amplitude of phase modulator M
dI	retardation modulation amplitude of phase modulator M1 (or C1)
dΔ	modulation of relative phase
dψ	modulation of relative amplitude
E	elliptic state of polarization incident on specimen
F	fast axis of retardation plate (also C, M, Q)
FC	Faraday cell
H	plane of incidence
I	locus of polarization states with equal irradiance transmitted by an analyzer
L	left-hand circular polarization
M	fast axis of retardation (phase) modulator; retardation modulator
m	azimuth of retardation modulator fast axis
P	polarizer transmission axis; polarizer
p	azimuth of polarizer transmission axis
P _{rot}	rotating polarizer
PP	uniaxial crystal, producing two orthogonally polarized beams

Q	fast axis of quarter-wave compensator; quarter-wave compensator
q	azimuth of quarter-wave plate fast axis
R	locus of modulated reflected polarization
S	specimen
Δ	physical parameter of elliptic polarization, relative phase between p and s components; change in relative phase upon reflection
δC	retardation of variable compensator
δQ	retardation of quarter-wave compensator
δl	retardation of compensator C1
γ	geometrical parameter of elliptic polarization, measured in the sense of rotation of the ellipse; $\tan \gamma =$ axial ratio
ψ	physical parameter of elliptic polarization, $\tan \psi =$ relative amplitude of p and s components
(ψ)	change in relative amplitude parameter ψ due to reflection
θ	geometrical parameter of elliptic polarization, azimuth of major ellipse axis

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Table I. Operating principles of non-compensating automatic ellipsometers.

Modulation	Measurement	Detection	Sequence of Components	References	Remarks
None	Off-null irradiance				
	start from extinction	continuous	P, S, Q, A	4	
	start from off-extinction	continuous	P, Q, S, A	5	
Rotating Analyzer	Phase and irradiance	phase-sensitive	P, S, A _{rot}	7-9	computation circuit (7)
			P, S, Q, A _{rot}	7,8	
		Fourier analysis	P, S, A _{rot}	6,10-14	on-line computer (11-14)
			P, Q, S, A _{rot}	11,13	automatic specimen alignment (11)
	Two phases	phase-sensitive	P, P _{rot} , S, A	19,20	
			P, S, A _{rot} , A	19,21	
Oscillating Analyzer	Phase and irradiance	Fourier analysis	P, S, FC, A	15	on-line computer
Retardation, photoelastic	Phase and irradiance	phase-sensitive	P, M, S, A	22	2 successive wavelength scans needed for 2 parameters
			P, M, A, S	23	computation circuit
			P, M, S, A	24	2 parameters measured simultaneously; on-line computer
			PP, M, S	26	differential; 2 specimens

Table II. Operating principles of compensating automatic ellipsometers.

Modulation	Detection	Compensation	Measurement	Sequence of Components	References	Remarks
Azimuth, electro-mech.	continuous	Electro- mechanical	Azimuths p and a	P, Q, S, A	28-30	Computer-operated; modulation slow
magneto-optical	Phase-sensitive	Magneto- optical	p and a	P, FC1, S, Q, FC2, A	31	2 Faraday cells for mod. and comp.
			p and a	P, FC1, Q, S, FC2, A	32	
		Manual	p and a	P, FC1, Q, S, FC2, A	54	measure 1 parameter only
			p and a	P, S, FC, Q, A	42	
opto-mech.	Phase-sensitive	Manual	p and a	P, S, Q, FC, A	45	rotating opt. active half-disks
			Azimuths		33	
Retardation (phase) electro-optical	Phase-sensitive	Electro- mechanical	Azimuths p, m1 and a, m2	P, M1, Q, S, M2, A	38	2 Pockel cells; 2 servomotors
			Azimuth p, Retardation δC	P, Q, M1, M2, C, S, A	37	2 Pockel cells; 2 servomotors
		Electro- optical	Retardations	P, S, C1, C2, Q, A	39	2 Pockel cells for mod. and comp.
Azimuth and Retardation	Phase-sensitive	Manual	Azimuths q and a	P, FC, M, S, Q, A	41	Faraday and photo-elastic cells

Table III. Performance of non-compensating automatic ellipsometers.

Operating principle	Modulation Frequency and Amplitude	Slew Rate deg/sec	Resolution deg	Dynamic Range deg	Reference	Remarks
Off-null Irradiance	none	ψ 500** Δ 1000**	ψ 0.01 Δ 0.02	ψ 5 Δ 10	5	** based on time-constant 0.01 s; not suitable for λ scan
Rotating Analyzer						
Phase and Irradiance Meas.	50 Hz	θ 9000*	θ 0.01	θ 180	7	
	180°	γ 2250*	γ 0.01	γ 45		
	10 Hz**	θ 1800*	θ 0.0018†	θ 180	11	** 5 rps, 256 irradiance mens. per revolution; on-line Fourier analysis
	180°	γ 450*	γ 0.0018†	γ 45		† standard deviation, 10 revolutions (20 readings) per measurement; accuracy in Δ 0.1°, ψ 0.05°
Two Phase Measurements	10 Hz	θ 1800*	-	θ 180	12	512 meas. per revolution, 20 revolutions per measurement; on-line Fourier analysis; accuracy in Δ 0.1°
	180°	γ 450*	-	γ 45		
	74 Hz	θ 13500*	ψ 0.0005†	θ 180	13	† 1000 cycles per measurement; on-line Fourier analysis; u.v.--near i.r.
Retardation Modulation	180°	γ 3250*	Δ 0.001†	γ 45		
	100 Hz	θ 18000*	θ 0.002†	θ 180	20	near i.r. † 100 cycles per measurement
Retardation Modulation	180°	γ 4500*	γ 0.002†	γ 45		
	50 kHz	ψ 2250** Δ 9000**	1% 1%	ψ 45 Δ 180	22	** based on time-constant 0.02 s; near u.v.--near i.r.
Retardation Modulation	50 kHz	ψ 180** Δ 720**	ψ 0.0003† Δ 0.008†	ψ 45 Δ 180	24	** based on 4 readings/sec; on-line data analysis † short-term
	138°					

* based on single reading

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Table IV. Performance of compensating automatic ellipsometers.

Operating Principle	Modulation Frequency and Amplitude	Slew Rate deg/sec	Resolution deg	Dynamic Range deg	Reference	Remarks
Azimuth Modulat. and Comp.						
Electro-mechanical	single osc. 1.2°	ψ 3**	ψ 0.01	ψ 90	29	** based on 300 steps/sec, exclusive of 1.6s for nulling; computer-operated
		Δ 6**	Δ 0.02	Δ 360		
Magneto-optical	500 Hz* 0.15°†	ψ 470**	-	ψ 10	31	** theoretical limit due to inductance of solenoid, requires higher modula- tion frequency to reach † derived from circuit and solenoid characteristics
		Δ 940**	-	Δ 20		
	10kHz* 0.9°	ψ 1600**	ψ 0.04	ψ 51**	32	time-constant 0.001 s (10 modulations/reading) **time-constant 0.1 s
		ψ 0.33	ψ 0.0007**	ψ 51**		
		Δ 3200**	Δ 0.08	Δ 110**		
		Δ 0.66**	Δ 0.0014**	Δ 110**		
Magneto-optical modulat., mechanical comp.	380Hz	ψ 4**	ψ 0.0004	ψ 4	42	** based on 1 s response time;
	400Hz	θ 2** γ 3**	θ 0.0006 γ 0.001	θ 2 γ 3	45	** based on 1 s response time; manual compensation
Retardation Modulat. (electro-optical),						
Azimuth Compensat. (electro-mech.)	60Hz* 5°†	ψ 0.2	ψ 0.01	ψ 45**	38	** manual zone selection † estimated
		Δ 0.4	Δ 0.02	Δ 180**		
Retardation Compensat. (electro-optical†)	50Hz* 7°	ψ 90**	ψ 0.1†	ψ 90	39	** based on 1 sec response time † estimated † via servo-motors
		Δ 180**	Δ 0.2†	Δ 180		
Azimuth and Retard. Mod.						
Azimuth Compensat. (manual)	930Hz, 17kHz 2°, 180°	θ 180**	θ 0.02	θ 180	41	** based on 1 sec response time; frequency-separation of channels
		γ 90**	γ 0.02	γ 90		

* Phase-separation of control channels.

Figure Captions

Fig. 1. Poincaré sphere for representation of state of polarization.

(a) Grid for geometrical parameters, azimuth θ of major ellipse axis and axial ratio $\tan\gamma$, with γ positive ("northern hemisphere") for left-hand rotation. H-plane of incidence, L-left-hand circular pole. (b) Grid for physical parameters, relative phase Δ and relative amplitude $\tan\psi$. (c) Grid for retardation δC of a compensator with fast axis F (F replaced by Q for a quarter-wave plate, M for a modulator or C for a variable compensator). (d) Amplitude (square root of irradiance) $A'E$ of elliptic polarization E transmitted by analyzer A. Small circle I. locus of polarization states with equal transmitted irradiance.

Fig. 2. Off-null irradiance measurement. Sequence and azimuths of components P, Q (45°), S, A. (a) Polarizer off compensation; extinguished linear polarization A' , transmitted amplitude $A'E$ sensitive to changes in Δ . (b) Analyzer off compensation, transmitted amplitude $A'E$ sensitive to changes in ψ .

Fig. 3. Irradiance measurement with rotating analyzer. Sequence and azimuths of components P (45°), S, A (rot.). $A'E$ minimum transmitted amplitude, a' azimuth θ of major ellipse axis, double arrow indicates rotation of A' .

Fig. 4. Periodic variations in transmitted amplitude $A'R$ resulting from retardation modulator M with periodically variable retardation dM . Sequence and azimuths of components P (90°), M (45°), S, A (-45°). E - locus of elliptic polarization states incident on the specimen, R - locus of polarization states reflected from the specimen.

Fig. 5. Effect of azimuth modulation on transmitted irradiance.

Sequence and azimuths of components P, Q (45°), S, A.

(a) Modulation $d\phi$ of polarizer azimuth is equivalent to a modulation $d\Delta$ in relative phase of the restored linear polarization A'. Sequence of polarization states through an ellipsometer: P-Polarizer, Q-fast axis of quarter-wave plate of retardation δQ , E-elliptic state of polarization incident on specimen, Δ -change in relative phase parameter due to reflection, (ψ) -change in relative amplitude parameter ψ due to reflection, A'-restored linear polarization. (b) Modulation $d\alpha$ of analyzer azimuth is equivalent to a modulation $d\psi$ of relative amplitude of restored linear polarization A'.

Fig. 6. Modulation $d\phi$ of polarizer azimuth by use of a retardation modulator M with retardation amplitude dM . Sequence and azimuths of components P (0°), M (45°), Q (0°).

Fig. 7. Modulation $d\psi$ and $d\Delta$ of restored linear polarization A' by use of two retardation modulators M1 and M2 coupled (with 45° difference) to azimuths of polarizer and analyzer, respectively. Retardation amplitudes of modulators $d1$ and $d2$. Sequence and azimuths of components P, M1 ($p-45^\circ$), Q (45°), S, M2 ($a+45^\circ$), A.

Fig. 8. Use of two variable compensators C1 and C2 of fixed azimuth for compensation (retardation $\delta1$ and $\delta2$, respectively) and modulation (retardation amplitude $d1$ and $d2$). Sequence and azimuths of components P (45°), S, C1 (0°), C2 (45°), Q (45°), A (90°).

XBL 756-3335

Fig. 1

XBL 756-3336

Fig. 2

XBL 759-7247

Fig. 3

XBL 759-7248

Fig. 4

XBL 759-7249

Fig. 5

XBL 759-7251

Fig. 6

XBL759-7250

Fig. 7

XBL 759 - 7252

Fig. 8

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