Geometrical Optics

Robert E. Fischer, William H. Price, Warren J. Smith
Chairmen/Editors

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This volume is dedicated to the memory of William H. Price

February 3, 1985

GEOMETRICAL OPTICS

Volume 531

Conference Committee

Chairmen
Robert E. Fischer
Hughes Aircraft Company

William H. Price
William Price Associates

Warren J. Smith
Santa Barbara Applied Optics

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Session 1—Basic Principles
Robert E. Fischer, Hughes Aircraft Company

Session 2—Lens Design Background
William H. Price, William Price Associates

Session 3—Optical Systems Analysis
Robert R. Shannon, Optical Sciences Center/University of Arizona

Session 4—Aspects of Optical Engineering
Robert E. Fischer, Hughes Aircraft Company

Session 5—Special Optical Devices
Warren J. Smith, Santa Barbara Applied Optics

GEOMETRICAL OPTICS

Volume 531

INTRODUCTION

Geometrical optics has been and still is one of the foremost technologies in all of optics and optical engineering. With all of the advances in image processing, solid state detectors, tracking, and the like, we still require geometrical optics to create our imagery. And with these current and advancing trends in technology, the demands on the imaging system are becoming increasingly greater.

This critical review of technology on the subject of geometrical optics provides a broad and comprehensive treatment of the subject from basic first order principles through aberrations and design optimization, and ultimately to the hardware intensive area of mounting and alignment.

In the first session we present papers on basic principles, including glass technology, first order layout, aberration theory, and optical design methods. The second session covers the background of various lens design forms, including photographic objectives, infrared systems, mirror systems, and general optimization methods.

In the third session we discuss tradeoffs in optical system design, the eye in optical systems, stray radiation considerations, and radiometry and photometry. In the fourth session we present more engineering-related aspects of the technology including glass selection, mounting and alignment, and the establishment of a tolerance error budget.

In the fifth and final session we discuss special and contemporary applications including non-image forming systems, modern zoom lenses, holographic optical elements, and nonconventional design forms.

Included in the five sessions of this critical review are virtually all of the key subtechnologies which make up the fascinating and important field of geometrical optics.

We dedicate this critical review of technology to the memory of our close colleague and co-chairman, Bill Price.

Robert E. Fischer
Hughes Aircraft Company

Warren J. Smith
Santa Barbara Applied Optics

GEOMETRICAL OPTICS

Volume 531

Contents

ORIGINAL PAGE IS
OF POOR QUALITY

Conference Committee v

Introduction vi

SESSION 1. BASIC PRINCIPLES 1

531-01 **Optical glass technology,** A. J. Marker III, Schott Glass Technologies, Inc. 2

531-02 **First order optical system layout,** D. C. Sinclair, Sinclair Optics, Inc. 11

531-03 **Aberrations and their effects on images,** R. R. Shannon, Optical Sciences Ctr./Univ. of Arizona 27

531-04 **Optical design methods: your head as a personal computer,** D. Shafer, David Shafer Optical Design, Inc. 49

SESSION 2. LENS DESIGN BACKGROUND 59

531-05 **Development of the photographic objective,** R. Kingslake, Univ. of Rochester 60

531-06 **Optimization methodology,** M. J. Hayford, Optical Research Associates 68

531-07 **Optical design for the infrared,** R. E. Fischer, Hughes Aircraft Co. 82

531-08 **Mirror systems: engineering features, benefits, limitations and applications,** I. R. Abel, Honeywell Electro-Optics Div. 121

SESSION 3. OPTICAL SYSTEMS ANALYSIS 135

531-09 **The eye in optical systems,** D. Williamson, Ernst Leitz Canada Ltd. (Canada) 136

531-10 **Trade-offs in optical system design,** W. H. Price, William Price Associates 148

531-11 **Stray light control, evaluation, and suppression,** P. J. Peters, Aerospace Corp. 156

531-12 **Elements of radiometric and photometric calculations,** W. J. Smith, Santa Barbara Applied Optics 168

SESSION 4. ASPECTS OF OPTICAL ENGINEERING 177

531-14 **Glass selection in optical design,** M. J. Kidger, Kidger Optics Ltd. (England) 178

531-15 **Optical element mounting and alignment technique,** R. E. Hopkins, Optizon Corp. 187

531-16 **Fundamentals of establishing an optical tolerance budget,** W. J. Smith, Santa Barbara Applied Optics 196

SESSION 5. SPECIAL OPTICAL DEVICES 205

531-17 **Non-image-forming optical components,** P. R. Yoder, Jr., Perkin-Elmer Corp. 206

531-18 **The modern zoom lens for 35 millimeter photography,** E. Betensky, Opcon Associates, Inc. 221

531-19 **Optical system design using holographic optical elements,** M. J. Hayford, Optical Research Associates 241

531-20 **Unusual optical forms,** D. T. Moore, Univ. of Rochester 256

Addendum 264

Author Index 265

GEOMETRICAL OPTICS

Volume 531

Session 1

Basic Principles

Chairman
Robert E. Fischer
Hughes Aircraft Company

Optical glass technology

Alexander J. Marker, III

Research & Development, Schott Glass Technologies, Inc.
400 York Avenue, Duryea, Pennsylvania 18642

Abstract

Any critical review of the technology associated with geometrical optics must certainly include a discussion of optical glass. Optical glass is a material which is familiar to all optical designers; however, few designers are familiar with the manufacturing process. This article considers optical glass from a manufacturer's point of view, with the goal of presenting a perspective which may help the designer to better understand why all his desired properties cannot be fulfilled and what compromises must be made. Also discussed is the meaning of terms used to quantify the inhomogeneities found in optical glass.

Optical glass manufacturing

To begin, a brief outline of the optical glass manufacturing process will be helpful. This process dictates which optical glass properties are easy to achieve and which are almost impossible to achieve. The production process involves the following steps: Batching, melting, refining, stirring, forming, and annealing. Each of these steps will be discussed in turn.

Batching is the first step. The individual chemicals are properly measured and combined. For proper mixing the particle size of the various components should be matched as closely as possible in order to prevent batch segregation. Batch segregation can lead to fluctuations in the glass properties such as density and refractive index. The raw materials used for batching of high quality optical glass must be chemically pure, since common contaminants such as iron or transition metals can cause coloration or a shift in the UV cut-on characteristics of the glass. Once the batch is prepared it is taken to the melting unit.

During melting the initial batch reactions occur and a glass melt is formed. In the melt some pre-conditioning occurs, i.e., convection currents cause some blending of the batch material; also, any batch stones present have a chance to dissolve. There are two common types of melting.

Pot melting is a discontinuous process, i.e., the batch material is introduced, the initial batch reactions occur, followed by pre-conditioning. After the glass melt is formed, refining and stirring take place. The glass is then ready to be formed into the desired shape. The pot material can be either a metal such as platinum, or a ceramic material such as quartz or clay. The amount of glass produced in a pot varies with the availability of sizes in which the pot material can be fabricated. This puts a limit on the volume of glass which can be obtained in a casting. This may severely limit the sizes to which certain optical glass types can be manufactured.

Tank melting is a continuous process, i.e., batch is introduced into the intake end of the unit and conditioned glass is formed at the discharge end of the melter. The amount of glass produced in a tank per day may be on the order of tons, depending on the flow rate and the glass type. Since the process is continuous, the melt is pre-conditioned to an extent depending on the dwell time of the tank. The molten glass moves into the refiner and, then, the stirring section. After leaving the stirring section, the glass is ready for forming into the desired shape.

Tanks are generally constructed of refractory materials such as high density fused silica, AZS or other materials. The choice of ceramic refractory depends on the glass type to be melted.

The choice between using a pot or a tank for manufacturing the glass is determined by the viscosity curve of the glass, the batch composition and the interaction of the batch with the refractory materials. The size of the order for a particular glass type has little effect on the choice between tank or pot, since very few optical glasses can be made of equal quality in either.

The refining stage is the first step of the homogenizing process. This step is carried out at high temperatures where the viscosity of the glass is low, allowing bubbles to rise to the surface. Since high quality optical glass must be free from bubbles, the mixing and degasification step is very important. Refining agents such as Arsenic Trioxide are often added to the batch. As the batch reacts and the melt is formed, the Arsenic Trioxide is converted to Arsenic Pentoxide. At high temperatures the refining agents decompose and give off oxygen.

$$As_2O_5 \rightarrow As_2O_3 + O_2 \uparrow . \text{ (high temperature)} \quad (1)$$

The oxygen bubbles absorb other dissolved gasses in the melt, thus forming large bubbles which then rise faster to the surface.[1] The bubbles which remain in the glass melt, after refining, can be reabsorbed into the glass by the oxidation of Arsenic Trioxide as the temperature of the melt is lowered to the forming temperature.

The stirring stage is the second step in the homogenizing process. Stirring is generally carried out at a lower temperature than the melting and refining stages. The continuous stirring provides a thorough distribution of all components within the glass melt. This is very important for the elimination of striae and producing a uniform refractive index over the entire casting. During this stage any remaining soluble bubbles are re-absorbed into the melt. The melt is cooled slowly until the proper pour temperature is reached. This temperature is such that the viscosity of the glass is in the working range.

The homogenizing steps discussed above are applicable to either pot or tank melting. This process is critical for the production of inclusion and striae-free glass with uniform refractive index.

During the forming stage the conditioned glass is processed into the desired shapes, i.e., rods, slabs, strips, blocks or pressings. The forming process takes place at temperatures so that the viscosity of the glass is between 10^3 to 10^8 poise, depending on the desired shape.

There are two annealing processes, coarse annealing and fine annealing. Generally, high quality optical glass will be coarse annealed as a first step. The glass then can be initially inspected for inclusions and striae. After inspection, the glass is fine annealed to remove residual thermal stresses due to the forming process. The annealing cycle depends on the glass type, volume of the piece, and customer requirements.

In summary, the manufacturing process leads to the inhomogeneity found in optical glass. Also, the melting process defines the sizes to which glass blanks of good quality can be produced.

Selection of glass types

In selecting the proper glass for a particular system the designer should be aware of the availability of the glass types. This information is generally given in the optical glass catalogs of most suppliers (for example, see references 2, 3, 4, 6). Since I am most familiar with the Schott catalogs and codes, I will use these as an example. There are two code systems in use: in the large optical glass catalog, the preferred glasses are shown in red on the nd vs. νd plot; in the small pocket catalog the preferred glasses appear in dark, bold type. Preferred glasses are ones which are often melted and are always available from stock. The glass types making up this category are determined by historical usage and continued high demand. Other optical glass manufacturers use similar codes. The small catalog also lists, in regular or lighter type, standard glasses. These are melted at regularly scheduled intervals and are generally available from stock. The glasses with an asterisk are specially-ordered glasses. These glass types are melted upon request only. Again, the continued usage, and/or ease of production, determine into which category the glass is placed. Table I lists the glass types according to the categories: preferred, standard, and special order.

Large size blanks, especially in high quality grades, may not be available in all glass types. The inability to produce large blanks of certain glass types is a result of the chemical nature of the glass, i.e., whether the glass is pot or tank meltable, prone to devitrification or large index variations. Table II lists the maximum-produced volumes of the various glass types for the normal quality category. Precision quality glass generally is available in smaller volumes only. Of course, most glass manufacturers will be glad to try to produce larger pieces and/or better quality than is customarily available, but this involves process development which is costly and is reflected in the price of the desired glass.

Specifying glass

When the designer specifies glass, the following items should be considered carefully:

Striae

Hard striae are localized chemical composition fluctuations within the glass matrix. This type of striae contains a composition whose refractive index is very different from that of the glass matrix. The index fluctuation is over a small dimension, typically, 10^{-2} to 10^{-1} cm, see Figure 1.[7] In the glass matrix the striae appears as parallel threads, see Figure 2.

Table III lists glass types which generally contain striae when manufactured. This information is listed in the manufacturer's catalogs.[2,3,4,5] It should be noted that this is a composite list, and not all manufacturers encounter striae problems with the same glass types. Thus, if a system calls for a glass with precision striae grade, i.e., no visible striae, special production melts of these glasses will be required. This problem should be discussed with the manufacturer in order to ascertain whether it is possible to manufacture the glass to your striae specifications. The glass types are expressed in Schott codes except where equivalent glasses are not manufactured by Schott. The MIL specification MIL-G174A is used to compare the manufacturer's striae grades to an accepted standard.

Optical homogeneity

Soft striae, also called global inhomogeneity, are due to fluctuations in chemical composition within the blank; however, the inhomogeneity is extended in space, typically 10^{-1} to 150 cm.[7] This inhomogeneity may extend over the whole aperture of the optical element, see Figure 3. This type of striae affects the image quality to a larger extent than does the hard striae. The homogeneity grades listed in optical catalogs are for these extended, or global, inhomogeneities (see Table IV). This type of inhomogeneity is generally documented interferometrically.

The index variation given on a test certificate is for the direction of general use, i.e., the index variation is in a plane perpendicular to the optical axis. This information is usually sufficient. However, for certain applications such as prisms and some very thick lenses, the index variation in two mutually perpendicular directions is needed and should be specified. For example, a glass blank which shows a $\Delta n_d = \pm 1 \times 10^{-6}$ in one direction when viewed at right angles may show a $\Delta n_d = \pm 2 \times 10^{-6}$, which is one grade lower in homogeneity.

Tolerances of optical properties

The values of refractive index and dispersion listed in the manufacturer's catalogs[2,3,4,5] are based on results averaged over many melts. For any given melt, the maximum variation of n_d from the value listed in the catalog is typically ±0.001 and the Abbe Value (ν_d) varies at most ±0.8%. If closer values of index and/or dispersion are required, most manufacturers can provide different tolerance grades. The best tolerance grade for n_d is ±0.0002 and for the Abbe Value the best tolerance is generally ±0.2%. Some manufacturers may be willing to produce glass to even tighter tolerances; however, this requires a selection process which may adversely affect the price.

Stress birefringence

The residual stresses within the glass blank result from differential cooling during the forming and/or the annealing process. These stresses cause optical stress birefringence. The birefringence, or the difference in the refractive index between light polarized parallel to and perpendicular to the applied stress, is used as a measure of the residual stress in the glass. For coarse annealed optical glass the stress birefringence is about 75 nm/cm or less, which for BK-7 corresponds to a residual stress of 273.7 N/cm^2. Fine annealed glass has a residual birefringence of $\leq$10 nm/cm; for BK-7 this corresponds to a residual stress $\leq$36.5 N/cm^2.

The birefringence specification must be consistent with the homogeneity-grade specification. For example, if one specifies BK-7 of homogeneity group H-4, i.e., $\Delta n_d \leq \pm 1 \times 10^{-6}$, then the birefringence must be $\leq$10 nm/cm, otherwise the interferogram is distorted due to the residual stress in the glass and the optical homogeneity cannot be accurately determined. For all commonly manufactured blanks of sizes less than 600 mm in diameter and 100 mm in thickness, glass with birefringence greater than 10 nm/cm is considered coarse or commercially-annealed glass; fine annealed glass is in the range $\leq$10 nm/cm. Special precision annealing cycles can be carried out to reduce the birefringence to the 4 to 6 nm/cm range. For blanks larger in diameter than 600 mm and thicknesses greater than 100 mm, the birefringence specification should be reviewed with the manufacturer.

Bubbles

The bubble content of a glass is characterized by calculating the total bubble cross-sectional area in mm^2 per 100 cm^3 of glass. All inclusions such as tank or batch stones and crystals are counted as bubbles. Thus, in reality, this is an inclusion specification. The bubble/inclusion specification only includes "particles" larger than 0.05 mm (see Table V). For certain applications, for example laser glass, this criteria is not restrictive enough. Two or more bubbles within a circle of radius equal to 1/5 of the diameter of the blank is considered an accumulation of bubbles. Accumulations of bubbles are not allowed and the piece is rejected.[3] The total cross-section listed in the specification may be due to one large or several small bubbles as long as the accumulation criteria is met. The inclusions result from the melting and/or forming process. The bubbles generally result from insufficient refining.

Optical glasses for laser systems

Laser glasses are specialty optical-quality glasses of the highest precision and homogeneity. The base composition for the laser glasses is usually phosphate or silicate with Nd^{+3} as the most common active laser ion. The lasing wavelength for Nd^{+3} is nominally 1.06 µm; however, this value is shifted slightly to shorter wavelength for the phosphate glasses. There is a wide variety of laser glasses, each designed for different applications. One should consult the manufacturer's literature for further information[10,11,12]. Generally speaking, the phosphate-base laser glasses have a lower temperature coefficient of optical path length and a smaller effective linewidth than silicate-based glasses. The induced emission cross-section for phosphates, in most cases, is higher than silicates.

Er^{+3} is available as the active laser ion in a phosphate glass composition from at least one manufacturer.[12] In the host glass, the Er^{+3} ion lases at 1.54 µm, which is considered eye-safe. The Er glass is a possible material for eye safe laser rangefinders.

Optical glass manufacturers offer a broad range of specialty glass products to be used for laser-related applications. The lenses, beamsplitters, windows, and mirror substrates require a wide variety of homogeneous, high damage threshold optical glasses. A homogeneity grade of $\Delta n_d = \pm 1 \times 10^{-6}$ and precision-grade striae are required for these applications. For large systems such as the NOVA laser at LLNL, laser-grade BK-7 had to be supplied in blanks of this quality up to one meter in diameter.

An important parameter in designing laser systems is the maximum energy density the optical glass can withstand before damage of the element occurs. There are two types of damage which generally occur in optical glasses. Point-like damage appears as isolated damage sites along the beam path. These damage sites are caused by absorbing centers present in the glass. The filamentary or thread-like damage is continuous damage along the beam path, which starts first at the rear surface. This damage is due to self-focusing of the beam. Glasses with high non-linear refractive indices have lower threshold values for filamentary damage than for point-like damage. A paper by Hack and Neuroth[13] gives data on many optical and filter glasses. These glasses were exposed to a 3-nsec pulse from a Nd:YAG glass laser. The designer should contact the manufacturers if he has any questions or concerns about using a particular glass type in a laser system.

Harmonic conversion of the Nd:glass laser fundamental to produce shorter wavelengths has resulted in the need for special filter glasses of sizes, optical homogeneity, and transmission properties not available in conventional filters. Beam filters up to 90 cm in diameter are required for huge fusion lasers, with homogeneity equivalent to that of the highest quality optical glass (see Table VI). Also, laser damage and thermal shock considerations require volume absorption, thus these filters must be much thicker than conventional filter glasses.[14,15]

Conclusion

The chemical composition of the glass in conjunction with the required production method determines the size of the blank and the quality of the glass which is achievable. Historical usage and continued demand determine the category, preferred, standard, or special order, into which the optical glass is placed. If a newly-designed system requires special melted glasses, glasses which must be specially manufactured to yield precision striae grades in glass types which are prone to striae, or blanks larger and/or in higher quality than one customarily produces, the cost of the glass will likely increase. When specifying glass, some important parameters to keep in mind are striae grades, homogeneity requirements, index and dispersion variations, birefringence, and the bubble/inclusion requirement.

As an example of the application of high quality optical glass, laser systems were discussed. An important design parameter for laser applications is the damage threshold value of the optical glass. Depending on the system, this parameter may severely limit the designer's choices of optical glasses. Also, a new family of filter glasses of high optical quality has been developed for laser systems.

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Table I
Glass Categories[2,3,6]

Preferred Glass Types					
FK-1	SK-5	LaKN-6	BaFN-10	BaSF-2	SF-5
FK-5	SK-6	LaKN-7	BaFN-11	BaSF-10	SF-6
PK-2	SK-7	LaK-8	BaF-13	BaSF-51	SF-8
PSK-3	SK-10	LaK-9	BaF-50	BaSF-52	SF-10
BK-1	SK-11	LaK-10	BaF-51	LaFN-2	SF-11
BK-7	SK-14	LaKN-12	BaF-52	LaFN-3	SF-12
BaLKN-3	SK-15	LaKN-13	LF-5	LaFN-7	SF-14
K-5	SK-16	LaKN-16	LF-7	LaFN-21	SF-15
K-7	SKN-18	LaK-21	F-1	LaF-22	SF-18
K-10	KF-9	LaKN-22	F-2	LaF-23	SF-19
ZNK-7	BaLF-4	LLF-1	F-4	LaSFN-3	SF-53
BaK-1	BaLF-5	LLF-2	F-5	LaSFN-30	SF-55
BaK-2	SSK-2	LLF-6	F-6	SF-1	SF-56
BaK-4	SSK-4	BaF-3	F-7	SF-2	SF-57
SK-2	SSK-5	BaF-4	F-8	SF-3	SFN-64
SK-4	SSKN-8	BaF-8	BaSF-1	SF-4	KzFSN-4
Standard Glass Types					
FK-51	K-50	BaLF-50	F-9	LaFN-28	SF-59
FK-52	ZK-1	SSK-3	FN-11	LaSFN-9	SF-63
FK-54	ZK-5	SSK-50	F-14	LaSFN-15	SFL-6
PK-3	BaK-5	SSK-51	BaSF-6	LaSFN-18	SFL-56
PK-50	BaK-50	LaK-11	BaSF-13	LaSFN-31	TiFN-5
PK-51	SK-3	LaKN-14	BaSF-57	LaSF-32	KzF-1
PSK-2	SK-12	LaK-28	LaFN-8	LaSF-33	KzF-2
PSK-52	SK-13	LaK-31	LaF-9	SF-9	KzFSN-2
PSK-53	SK-51	LaKL-21	LaFN-10	SF-13	KzFSN-5
UBK-7	KF-3	BaF-9	LaFN-11	SF-16	KzFSN-7
BK-10	KF-6	LF-8	LaF-20	SF-54	LgSK-2
K-3	KF-50	F-3	LaFN-24	SF-58	
Specially-produced Glass Types					
PK-1	SK-9	LaKN-20	LF-6	LaSFN-7	TiF-2
PSK-50	SK-19	LLF-3	F-13	LaSFN-8	TiF-3
BK-3	SK-20	LLF-4	F-15	LaSF-11	TiF-4
BK-6	SK-52	LLF-7	BaSF-5	LaSF-13	TiF-6
BK-8	KF-1	BaF-5	BaSF-12	SF-7	TiSF-1
BaLK-1	BaLF-3	BaFN-6	BaSF-14	SF-17	KzF-6
K-4	BaLF-6	BaF-12	BaSF-50	SF-50	KzF-51
K-11	BaLF-8	BaF-53	BaSF-54	SF-51	KzF-26
UK-50	BaLF-51	BaF-54	BaSF-55	SF-52	KzFS-8
K-51	SSK-1	LF-1	BaSF-56	SF-61	KzFSN-9
BaK-6	SSK-52	LF-2	LaF-13	SF-62	
SK-1	LaK-23	LF-3	LaF-25	TiK-1	
SK-8	LaKN-17	LF-4	LaF-26	TiF-1	

Table II
Maximum Volume of Glass Produced for the Normal or Standard Quality Grade[6]

≤200 cm³	LaSFN-7	LaSFN-31	TiF-6			
≤500 cm³	LaSFN-9	LaSFN-13	LaSFN-18	TiK-1	TiF-2	TiF-4
	LaSF-11	LaSFN-15	LaSFN-30	TiF-1	TiF-3	TiSF-1
						LgSK-2
≤1000 cm³	FK-1	SK-55	LaKN-20	LaFN-24	LaSF-8	TiFN-5
	FK-54	BaLF-3	BaSF-50	LaF-25	LaSF-32	
	PSK-50	BaLF-6	BaSF-55	LaF-26	LaSF-33	
	K-4	LaLF-8	LaFN-7	LaSFN-3	SF-59	
≤3000 cm³	FK-3	K-3	LaK-10	BaSF-57	LaF-22	SFL-6
	FK-51	K-11	LaK-11	LaFN-2	LaF-23	SFL-56
	FK-52	SK-13	LaK-23	LaFN-3	LaFN-28	KzF-6
	PK-51	SK-51	LaK-28	LaFN-8	SF-50	KzFSN-7
	PSK-52	SK-52	LaK-31	LaF-9	SF-51	KzFS-8
	PSK-53	KF-1	LaKL-21	LaFN-10	SF-52	KzFSN-9
	BK-3	BaLF-51	LLF-4	LaFN-11	SF-58	
	BK-8	LaK-8	BaSF-14	LaF-13	SF-63	
	BaLK-1	LaK-9	BaSF-54	LaFN-21	SFN-64	
≤10,000 cm³	PK-1	SSK-1	BaF-3	BaSF-52	SK-11	BaF-53
	PK-5	SSK-50	BaF-12	BaSF-56	SK-12	BaF-54
	PSK-3	SSK-51	BaF-13	SF-54	SK-20	LF-6
	BK-10	SSK-52	BaF-50	SF-55	KF-3	FN-11
	K-10	LaKN-6	F-15	SF-56	KF-6	F-13
	BaK-6	LaKN-7	BaSF-2	SF-57	LaKN-12	LaF-20
	SK-1	LaKN-22	BaSF-5	SF-61	LaKN-13	SF-13
	SK-9	LLF-3	BaSF-12	KzF-1	LaKN-14	SF-16
	KF-9	LLF-6	BaSF-13	KzFS-1	LaKN-16	SF-17
	KF-50	LLF-7	BaSF-51	KzFSN-2	LaK-21	KzFSN-5
						KzFS-6
≤30,000 cm³	FK-5	SK-6	SSK-5	BaFN-11	F-14	SF-11
	PSK-2	SK-7	SSKN-8	BaF-51	BaSF-1	SF-14
	ZK-1	SK-8	LLF-1	BaF-52	BaSF-6	SF-15
	ZK-5	SK-10	LLF-2	LF-1	BaSF-10	SF-18
	BaK-1	SKN-18	BaF-4	LF-2	SF-1	SF-19
	BaK-2	SK-19	BaF-5	LF-3	SF-3	SF-53
	BaK-5	BaLF-50	BaFN-6	LF-4	SF-4	SF-62
	BaK-50	SSK-2	BaF-8	LF-7	SF-7	KzFSN-4
	SK-3	SSK-3	BaF-9	LF-8	SF-9	
	SK-5	SSK-4	BaFN-10	F-1	SF-10	
≤80,000 cm³	PK-3	K-51	SK-14	BaLF-5	F-6	SF-5
	BaLKN-3	BaK-4	SK-15	F-3	F-7	SF-6
	K-7	SK-2	SK-16	F-4	F-8	SF-8
	UK-50	SK-4	BaLF-4	F-5	SF-2	SF-12
>80,000 cm³	PK-2	BK-6	UBK-7	K-50	LF-5	KzF-2
	BK-1	BK-7	K-5	ZKN-7	F-2	

Table III

Difficult Glass: The following glass types are difficult to produce without striae[2,3,4,5]

FK-1	FK-01	PSK-1	F-16	LaSFN-31	TiF-4
FK-3	FCD-10	PSK-50	BaSF-54	FDS-10	TiFN-5
FK-5	PK-1	PSK-52	LaSFN-9	TiK-1	TiF-6
FK-51	PK-5	PSK-53	LaF-13	TiF-1	TiSF-1
FK-52	PC-51	KF-8	LaSF-13	TiF-2	KzF-6
FK-54	PK-51	LLF-8	LaSFN-18	TiF-3	LgSK-2

Table IV

Homogeneity Grades[2,-,5]

Max. Variation of n_d Value	Homogeneity Groups Schott/Hoya	Ohara
$\pm$ 20 x 10^{-6}	H-1	A-20
$\pm$ 5 x 10^{-6}	H-2	A-5
$\pm$ 2 x 10^{-6}	H-3	A-2
$\pm$ 1 x 10^{-6}	H-4	A-1

Table V

Bubble Classes (-, 4, 5)

Total cross-section area* 100 cm^3 of glass	Bubble Class Code Schott	Hoya	Ohara
0 - 0.029	BO	1	1
0.03 - 0.10	B1	1	1
0.11 - 0.25	B2	2	2
0.26 - 0.50	B3	3	3
0.50 - 0.99	--	4	-

*The cut-off values for bubble classes are approximate values for comparison only.

Table VI

Optical Properties Required for Laser Filters

Filters

homogeneity	H-3 to H-4 quality
birefringence	≤10 nm/cm
striae	grade A or better

$1\omega/2\omega$ beam dump

(BG-38A Schott; DFF-1 Hoya)

Wavelength	Internal Transmission (for 2 cm thickness) %
1ω	2
2ω	98

3ω beam dump

(Closest commercially-available TFF-1 Hoya)

Wavelength	Internal Transmission (for 1.5 cm thickness) %
1ω	4
2ω	1
3ω	97

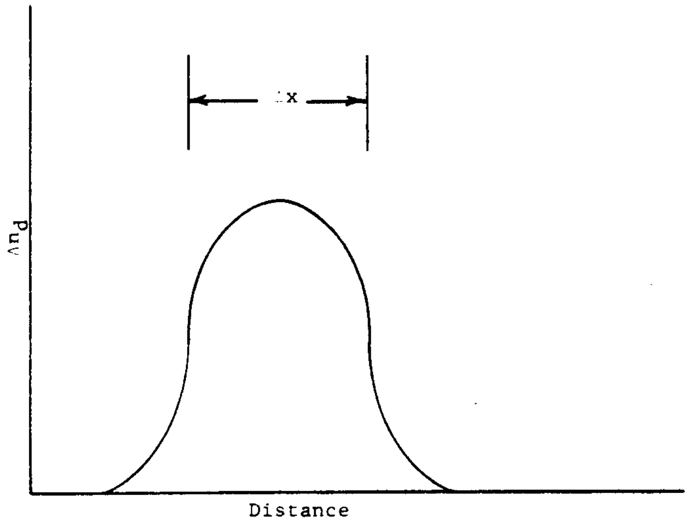

Figure 1. Index fluctuation as a function of distance for hard striae with $10^{-2} \leq \Delta x \leq 10^{-1}$ cm.

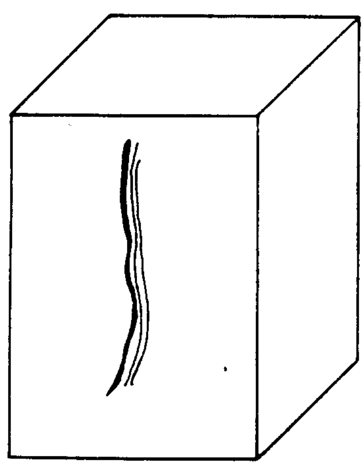

Figure 2. Schematic representation of parallel striae in a piece of optical glass.

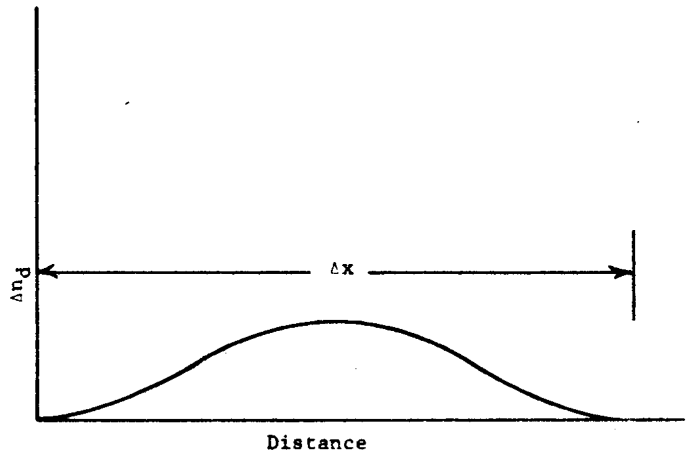

Figure 3. Index fluctuation as a function of distance for soft striae with $10^{-1} \leq \Delta x \leq 150$ cm.