## Index

| 35-mm film, 239 3-D, 235 high-definition television, 236 movie, 236 viewing, 236 | Airy disk, 41, 87, 120, 158, 200, 212, 215, 220 Alhazen, 6 alignment telescope, 167 aluminum coating, 135 Amici, Giovanni, 10 |
|--|---|
|  | angle solve, 73   |
| Abbe   | angular resolution limit, 159   |
| Ernst, 10  | antireflection coating, 179   |
| v number, 174  | broadband, 182, 183   |
| aberration   | diamond, 182  |
| chromatic, 105, 115  | single-layer, 183   |
| comatic, 108   | multilayer, 180   |
| curves, 117, 150, 200, 215   | aperture, 41  |
| monochromatic, 113   | stop, 49, 153   |
| off axis, 105  | apochromat, 96  |
| on-axis, 105   | apochromatic  |
| spherical, 105, 128  | lens design, 212  |
| accommodation, 191   | doublet, 217  |
| achromat, 96   | aqueous, 189  |
| achromatic   | Aristotle, 5  |
| cemented doublet, 159  | arthroscope, 169  |
| doublet, 113   | aspheric  |
| acrylic, 185   | infrared lenses, 139  |
| actual magnification numbers, 148  | surfaces, 136, 138, 182–183   |
| aerial image modulation (AIM), 91,   | astigmatism, 108, 110, 112, 128,  |
| 193  | 192, 200, 202, 223  |
| afocal system, 91  | astrophotography, 162   |
| air-spaced doublet, 124, 128, 129,   | athermalization, 185  |
| 213  | autocollimator, 167   |
| air-to-glass interface, 179  | axial color, 113, 124, 128  |
|  | axial travel per diopter, 155   |

| Bacon, Roger, 6                            | color (continued)                 |
|--|-----------------------------------|
| baffles, 202                               | primary, 114                      |
| barrel shape, 112                          | secondary, 114                    |
| Bausch and Lomb, 14                        | coma, 107, 128                    |
| binoculars, 163                            | compact disk, 236                 |
| Porro prism, 140, 164                      | compound magnifier, 155           |
| BK7 glass, 72, 175                         | concave aspheric shape, 227       |
| blur circle, 103                           | conic constant, 226, 227, 266     |
| borescope, 169                             | contrast, 150                     |
| flexible, 172                              | convergence, 235, 236             |
| Bradley, James, 11                         | Cooke triplet, 13, 220            |
| brightness, 259                            | cornea, 189                       |
| bubbles, 177                               | Corning, 178                      |
| ,  | cosmetic finish, 130              |
|  | critical angle, 143               |
| camcorder, 241                             | crown glass, 124, 175             |
| digital, 241                               | <b>G</b> , ,                      |
| camera obscura, 6                          |                                   |
| cataracts, 192                             | Daguerre, Louis, 10               |
| cc (conic constant), 266                   | dark ring, 45, 120                |
| CD (compact disk), 236                     | derotation prism, 144             |
| CD-ROM (compact disk, read-only            | design                            |
| memory), 241                               | documentation, 217                |
| cemented doublet, 124                      | evaluation, 222                   |
| Chance-Pilkington glass company,           | detail lens drawing, 128, 135     |
| 14   | deviating prism, 142              |
| change in index with temperature,          | diamond                           |
| 177  | coating, 182                      |
| Chevalier, Charles, 10                     | point machining, 138              |
| chief ray, 19, 54, 117                     | diffraction, 40                   |
| "chip in the tip", 171                     | modulation transfer function, 217 |
| chromatic aberration, 40, 96               | analysis, 208                     |
| CinemaScope, 18, 236                       | diffraction limited, 132, 196     |
| Cinerama, 18, 236                          | blur spot, 158                    |
| circle, 266                                | performance, 200                  |
| clear aperture, 134                        | digital                           |
| Cleartran, 183                             | camera, 157, 162, 241             |
| coefficient of linear expansion $\alpha$ , | photography, 239                  |
| 177–178                                    | recording system, 237             |
| collimated, 33                             | video, 239                        |
| beam, 210                                  | video disk (DVD), 237             |
| collimator, 166                            | player, 241                       |
| color                                      | diopters, 52                      |
| axial, 128                                 | dispersion, 39, 40, 174           |
| lateral 117 200–202                        |                                   |

| distortion, 202, 223                     | <i>f</i> /#, 56, 60, 156, 259, 261    |
|--|---------------------------------------|
| curve, 201                               | farsightedness, 192                   |
| negative, 112                            | fiber optics, 170                     |
| positive, 112                            | bundle, 172                           |
| Dolland, John, 10                        | field                                 |
| double-Gauss lens, 220                   | curvature, 108, 150                   |
| doublet, 123                             | curves, 200                           |
| air-spaced, 124, 128, 129                | flattener, 112, 221                   |
| cemented, 124                            | lens, 223                             |
| dry nitrogen, 69                         | sag curves, 112                       |
| durability, 136                          | stop, 50, 158, 165, 202               |
| DVD (digital video disk), 237            | size, 155                             |
| player, 241                              | field of view, 47, 60, 153, 156, 158, |
|  | 162, 163, 191                         |
|  | observed, 150                         |
| Earth's atmosphere, 181                  | vertical, 165                         |
| Eastern Optical Co., 16                  | final design optimization, 222        |
| Eastman Kodak, 14                        | finest resolvable pattern, 147        |
| Edmund                                   | Fizeau, Armand, 11                    |
| Scientific, 91                           | flint glass, 124, 175                 |
| Optics Inc, 97                           | focal system, 91                      |
| effective focal length (EFL), 47         | focus, 157, 235                       |
| electromagnetic spectrum, 21, 44         | adjustment, 197                       |
| electronic imaging, 239                  | range, 155                            |
| ellipse, 266                             | shift, 139, 144                       |
| encircled fractional energy, 119         | travel, 198                           |
| endoscope, 169, 236                      | Foucault, Jean Léon, 13               |
| ensquared energy diagram analysis,       | fovea, 191                            |
| 223                                      | fractional energy, 119                |
| ensquared fractional energy, 119         | Fraunhofer, Joseph, 9                 |
| entrance pupil, 49, 202, 220, 221        | free aperture, 130                    |
| equi-convex, 71                          | frequency, 24                         |
| Eratosthenes, 6                          | front surface mirror, 136             |
| erecting eyepiece, 166                   | fused                                 |
| Euclid, 5                                | quartz, 178                           |
| exit pupil, 49, 153, 158, 162, 202       | silica, 173, 178                      |
| exposure factors, 261                    |                                       |
| exposure value ( $E_{\nu}$ ) system, 259 |                                       |
| eye                                      | Galilei, Galileo, 8                   |
| convergence, 232                         | Gaussian thin-lens formulas, 63       |
| relief, 162, 165, 202                    | germanium, 182                        |
| eyelens, 189                             | Giambattista della Porto, 7           |
| eyepiece, 124, 152                       | glare stops, 202                      |

| glass                                   | injection molding, 186                 |
|---|--|
| BK7, 72, 175                            | interpupillary distance, 163           |
| crown, 124, 175                         | iris, 189                              |
| flint, 124, 175                         | diaphragm, 49                          |
| SF1, 175                                | ISO rating, 261                        |
| identification number, 174              | 2,                                     |
| map, 174                                |  |
| gold coating, 136                       | Janssen, Hans, 10                      |
| Grimaldi, Francesco, 9                  | Janssen, Johannes, 7                   |
| ,                                       | Janssen, Zacharias, 10                 |
|   | jig alignment telescope, 167           |
| Hall, Chester Moor, 9                   | J-88                                   |
| Hastings cemented triplet, 150          |  |
| head prism, 170                         | k (conic constant), 266                |
| height solve, 73                        | Kepler, Johannes, 8                    |
| Herschel, Sir William, 11               | Kollmorgen                             |
| Hindle sphere, 227                      | Optical Company, 17                    |
| homogeneity, 176                        | Frederick, 15, 16                      |
| Hooke, Robert, 10                       | Troderick, 13, 10                      |
| HOYA, 15                                |  |
| Hubble Space Telescope, 19              | Lambda Research Corp., 72, 80          |
| human eye, 189                          | laparoscope, 169                       |
| Huygens, Christiaan, 8                  | laser range finder, 26, 169            |
| hyperbola, 266                          | lateral color, 117, 200–202            |
| hyperboloid, 226                        | law of                                 |
| hyperfocial distance, 66                | reflection, 30                         |
| hyperopia, 192                          | refraction, 9, 37                      |
| nyperopia, 192                          | Lee, H. W., 13                         |
|   | lens, 123                              |
| illuminance, 263                        | aberrations, 103                       |
| image                                   | apochromatic, 212                      |
| brightness, 60                          | data, 209                              |
| derotation, 140                         | design, 15, 205                        |
| evaluation, 205                         | double-Gauss, 220                      |
| plane, 56                               | equi-convex, 71                        |
| quality, 215, 220                       | field flattener, 112                   |
| reversal, 132                           | Hastings cemented triplet, 150         |
| size, 47                                | libraries, 89                          |
| imager lens, 220                        | null, 226, 227                         |
| implanted artificial lens, 192          | Petzval, 53, 82, 221                   |
| index of refraction, 174                | plano-convex, 71                       |
| infrared                                | thin, 47                               |
| energy, 181                             | simple, 123                            |
| materials, 188                          | mock-up stage, 70                      |
| systems, 136, 173, 181                  | specifications, 220                    |
| ~ , ~ + + + + + + + + + + + + + + + + + | ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~ |

| lens (continued)                    | monocular, 124, 164                   |
|-------------------------------------|---------------------------------------|
| speed, 47                           | moon, 161                             |
| light ray concept, 30               | illusion, 232                         |
| light rays, 28                      | mounting a mirror, 135                |
| light sources, 28                   | multilayer coatings, 180              |
| Lincoln Memorial, 150               | multispectral-grade zinc sulfide, 183 |
| linear expansion, 177               | myopia, 192                           |
| Lister, Joseph Jackson, 10          |                                       |
| loupe, 147                          |                                       |
| low-expansion materials, 178        | near-infrared spectral bandwidth, 210 |
|                                     | nearsightedness, 192                  |
| magnetic tapes, 237                 | negative lens element, 39             |
| magnification, 58, 93               | Newton, Isaac, 9                      |
| value <i>M</i> , 148                | Newtonian                             |
| magnifier, 148                      | equation, 198                         |
| magnifying glass, 147               | thin-lens formula, 63                 |
| marginal ray, 49, 54                | noninvasive surgical procedures,      |
| Maurolico, Francesco, 6             | 236                                   |
| maximum visual resolution, 161      | null lens, 226                        |
| mechanical length, 144              | numerical aperture, 56, 156           |
| melt data, 176                      |                                       |
| Michelson, Albert A., 13            |                                       |
| micromachined mirror, 137           | oblate spheroid, 227                  |
| micromachining, 138                 | obscuration, 41                       |
| microscope, 89, 152, 155            | observed field of view, 150           |
| magnification, 155                  | Ohara, 15                             |
| <i>MIL Handbook 141</i> , 144, 202  | optic nerve, 191                      |
| mirror, 130                         | optical                               |
| concave, 33                         | axis, 49                              |
| convex, 33                          | coatings, 15, 173                     |
| curved, 136                         | designer, 2, 77                       |
| flat, 30, 130                       | glass, 173                            |
| front surface, 136                  | illusion, 231                         |
| Mangin, 137                         | instrument, 147                       |
| micromachined, 137                  | material                              |
| replicated, 137                     | acrylic, 185                          |
| spherical, 226, 227                 | fused quartz, 178                     |
| mirror substrate, 131               | fused silica, 173                     |
| modern PC system, 75                | germanium, 182                        |
| modified symmetrical form, 202      | glass, 173                            |
| modulation, 150                     | plastic, 173, 185, 188                |
| modulation transfer function (MTF), | polystyrene, 185                      |
| 84, 103, 150, 159                   | Pyrex, 178                            |
| data, 128                           | silicon, 183                          |

| optical (continued)                | plano-convex, 71                     |
|------------------------------------|--------------------------------------|
| material (continued)               | plastic, 173                         |
| zinc selenide, 183                 | Plato, 5                             |
| zinc sulfide, 183                  | point-spread function, 88, 119       |
| micrometer, 167                    | polymethylmethacrylate, 185          |
| path difference, 196               | polystyrene, 185                     |
| error, 227                         | Ponzo illusion, 231                  |
| range finder, 142                  | Porro prism binoculars, 140, 164     |
| schematic, 209, 218, 225           | positive lens element, 37            |
| sight level, 166                   | postpolishing, 139                   |
| spectrum, 44                       | precision collimator, 209            |
| tooling instruments, 166           | primary color, 114                   |
| Optical Design for Visual Systems, | prism, 40, 139                       |
| 153, 202                           | Amici, 140                           |
| optimization, 207                  | delta, 140                           |
| procedure, 200                     | derotation, 144                      |
| stage, 213                         | deviating, 142                       |
| OSLO (Optics Software for Layout   | dove, 140                            |
| and Optimization), 80, 205         | Pechan, 140                          |
| OSLO-EDU, 72, 81, 205              | derotation, 144                      |
| overall length, 144                | penta, 140                           |
| Owens CERVIT, 178                  | Porro, 140                           |
|                                    | right-angle, 139                     |
|                                    | roof Pechan, 163, 200-202            |
| parabola, 265–266                  | producibility, 215                   |
| paraboloid, 226                    | projection television, 237           |
| paraxial solves, 213               | front, 239                           |
| Pechan derotation prism, 144       | rear, 239                            |
| performance evaluation, 215        | pseudostereo, 236                    |
| periscope, 18                      | Ptolemy, 6                           |
| "golf course", 169                 | pupil                                |
| submarine, 115, 169, 171           | entrance, 49, 202, 220, 221          |
| perspective, 232                   | exit, 49, 153, 158, 162, 202         |
| Petzval,                           | Pyramid of Cheops, 5                 |
| curvature, 108, 112                | Pyrex, 178                           |
| Joseph, 10, 15                     |                                      |
| lens, 53, 82, 221                  |                                      |
| photography, 239                   | radial energy distribution, 87, 103, |
| still, 239                         | 159                                  |
| photometry, 259                    | rainbow, 242                         |
| pincushion effect, 112             | ray                                  |
| plane                              | chief, 49, 54                        |
| image, 56                          | marginal, 49, 54                     |
| saggital, 51                       | ray-trace analysis, 222              |
| tangential, 51                     | reference coordinate system, 51      |

| reflecting coating, 135    | silicon, 183             |
|----------------------------|--------------------------|
| aluminum, 135              | silver coating, 135      |
| gold, 136                  | simple lens              |
| silver, 135                | mock-up stage, 70        |
| reflection,                | simple window, 37        |
| law of, 30                 | Sinclair                 |
| refraction, 35             | Optics, 80               |
| chief-ray, 117             | Doug, 80                 |
| index of, 35               | Smakula, Alexander, 15   |
| for water, 35              | Snell, Willebrord, 8     |
| law of, 9, 37              | Snell's law, 37          |
| relative illumination, 169 | solid model graphic, 84  |
| relay lens, 164            | Soveril, 14              |
| replication process, 137   | spectral                 |
| resolution, 192            | bandwidth, 212           |
| reticle, 165               | response curve, 212      |
| retina, 191                | weights, 213             |
| riflescope, 164            | spectrum                 |
| RKE® eyepiece, 97          | optical, 44              |
| Roemer, Olaf, 11           | visible, 44              |
| roof                       | electromagnetic, 21, 44  |
| angle, 132                 | speed of light, 24       |
| mirror, 132                | in air, 24               |
| Pechan prism, 163, 200–202 | spherical                |
| prism, 132                 | aberration, 105          |
| Rudolph, Paul, 10, 13      | surface, 136             |
| -                          | test mirror, 227         |
|                            | split-crown element, 124 |
| sag, 265                   | spot diagram, 103, 159   |
| sagittal plane, 51         | stage micrometer, 157    |
| scale focal length, 82     | standard illuminants, 29 |
| scene brightness, 261      | stereo                   |
| Schott                     | effect, 164              |
| Glass Works, 14            | image, 172               |
| Optical Glass Company, 174 | stereoscope, 235         |
| Zerodur, 178               | still photography, 239   |
| Schroeder, 10              | Stonehenge, 5            |
| scientific notation, 23    | Strehl ratio, 119        |
| scratch/dig, 130           | striae, 177              |
| secondary color, 96, 114   | Strong, John, 15         |
| seeds, 177                 | styrene, 185             |
| semiapochromat, 96         | surface                  |
| sensitivity, 259           | reflection loss, 179     |
| SF1 glass, 175             | sag, 265                 |
| shutter speed, 261         | surveying, 166           |

| tangential plane, 51              | visual                       |
|-----------------------------------|------------------------------|
| Taylor, H. Dennis, 13, 15         | acuity, 192                  |
| telescope, 152, 158               | as a function of field angle |
| alignment, 167                    | 191                          |
| design, 206                       | resolution capability, 193   |
| jig alignment, 167                | response curve, 152          |
| magnification, 158                | system, 231                  |
| terrestrial, 163                  | test chart, 193              |
| television                        | Vitello, 6                   |
| projection, 237                   | vitreous, 191                |
| front, 239                        | von Liebig, Justus, 9        |
| rear, 239                         | wavefront, 27                |
| three-dimensional high-           | curves, 215                  |
| definition, 236                   | error, 196, 202, 210         |
| test equipment, 229               | wavelength, 21, 212          |
| theodolite, 166                   | wedge, 142                   |
| thermal expansion, 178, 215       | tolerance, 219               |
| thin lens, 47                     | weights, 212                 |
| formulas, 61                      | worst-case prediction, 219   |
| Newtonian, 63                     | 1                            |
| Gaussian, 63                      |                              |
| power, 52                         | X axis, 51                   |
| third dimension, 235              | ,                            |
| high-definition television, 236   |                              |
| movie, 236                        | <i>Y</i> axis, 51            |
| viewing, 236                      | Young, Thomas, 11            |
| time, 259                         | 2)                           |
| Todd AO, 236                      |                              |
| tolerance analysis, 130           | Z axis, 51                   |
| tolerances, 88                    | Zeiss Tessar lens, 13        |
| tolerancing process, 218          | zinc                         |
| total                             | selenide, 183                |
| internal reflection, 142          | sulfide, 183                 |
| path, 144                         | 20000000                     |
| transit, 166                      |                              |
|                                   |                              |
|                                   |                              |
| van Leeuwenhoek, 10               |                              |
| VCR (videocassette recorder), 241 |                              |
| video camera, 241                 |                              |
| videocassette recorder (VCR), 241 |                              |
| vignetting, 73, 84, 169, 223      |                              |
| visible spectrum, 23, 44          |                              |
| * * *                             |                              |

## **About the Author**



Bruce H. Walker, founder and president of Walker Associates, has been active in the fields of optical engineering and lens design since 1960. He was an optical engineer and lens designer at General Electric from 1960 until 1971. While at GE, he received four patents for specialized lens designs that were used in the medical field. Mr. Walker was with the Electro-Optical Division of Kollmorgen Corporation from 1971 until 1991. He joined Kollmorgen as a senior optical engineer and was promoted to manager of optical engineering in 1981. At Kollmorgen he was a key contributor to all ongoing projects, including military sights.

foreign and domestic submarine periscope programs, and the photonics mast, which was developed in the 1980s. Mr. Walker was a member of the editorial advisory board of the Laurin Publishing Company from 1970 until 1999. During those years he contributed more than 30 technical articles to the pages of *Photonics (Optical) Spectra*, while also making numerous significant contributions to the *Photonics Industry Directory*. In 1995 Mr. Walker authored the first edition of *Optical Engineering Fundamentals*. In 2000 he followed with *Optical Design for Visual Systems*, also available from SPIE as a part of their popular tutorial text series. Since 1991 Mr. Walker has worked as an independent optical design consultant, specializing in providing unique solutions to a variety of optical engineering problems and to the generation of numerous specialized lens designs.