

PROCEEDINGS OF SPIE

Advances in Optical Thin Films III

Norbert Kaiser
Michel Lequime
H. Angus Macleod
Editors

2–3 September 2008
Glasgow, United Kingdom

Sponsored by
SPIE Europe

Cosponsored by
Scottish Optoelectronic Association (United Kingdom)

Cooperating Organisations
EFDS—Europäische Forschungsgesellschaft Dünne Schichten e.V. (Germany)
Institute of Photonics (United Kingdom)
OpTIC Technium (United Kingdom)
WOF—Welsh Optoelectronics Forum (United Kingdom)

Published by
SPIE

Volume 7101

Proceedings of SPIE, 0277-786X, v. 7101

SPIE is an international society advancing an interdisciplinary approach to the science and application of light.

The papers included in this volume were part of the technical conference cited on the cover and title page. Papers were selected and subject to review by the editors and conference program committee. Some conference presentations may not be available for publication. The papers published in these proceedings reflect the work and thoughts of the authors and are published herein as submitted. The publisher is not responsible for the validity of the information or for any outcomes resulting from reliance thereon.

Please use the following format to cite material from this book:

Author(s), "Title of Paper," in *Advances in Optical Thin Films III*, edited by Norbert Kaiser, Michel Lequime, H. Angus Macleod, Proceedings of SPIE Vol. 7101 (SPIE, Bellingham, WA, 2008) Article CID Number.

ISSN 0277-786X
ISBN 9780819473318

Published by

SPIE

P.O. Box 10, Bellingham, Washington 98227-0010 USA
Telephone +1 360 676 3290 (Pacific Time) · Fax +1 360 647 1445
SPIE.org

Copyright © 2008, Society of Photo-Optical Instrumentation Engineers

Copying of material in this book for internal or personal use, or for the internal or personal use of specific clients, beyond the fair use provisions granted by the U.S. Copyright Law is authorized by SPIE subject to payment of copying fees. The Transactional Reporting Service base fee for this volume is \$18.00 per article (or portion thereof), which should be paid directly to the Copyright Clearance Center (CCC), 222 Rosewood Drive, Danvers, MA 01923. Payment may also be made electronically through CCC Online at copyright.com. Other copying for republication, resale, advertising or promotion, or any form of systematic or multiple reproduction of any material in this book is prohibited except with permission in writing from the publisher. The CCC fee code is 0277-786X/08/\$18.00.

Printed in the United States of America.

Publication of record for individual papers is online in the SPIE Digital Library.

SPIE 
Digital Library

SPIDigitalLibrary.org

Paper Numbering: Proceedings of SPIE follow an e-First publication model, with papers published first online and then in print and on CD-ROM. Papers are published as they are submitted and meet publication criteria. A unique, consistent, permanent citation identifier (CID) number is assigned to each article at the time of the first publication. Utilization of CIDs allows articles to be fully citable as soon they are published online, and connects the same identifier to all online, print, and electronic versions of the publication. SPIE uses a six-digit CID article numbering system in which:

- The first four digits correspond to the SPIE volume number.
- The last two digits indicate publication order within the volume using a Base 36 numbering system employing both numerals and letters. These two-number sets start with 00, 01, 02, 03, 04, 05, 06, 07, 08, 09, 0A, 0B ... 0Z, followed by 10-1Z, 20-2Z, etc.

The CID number appears on each page of the manuscript. The complete citation is used on the first page, and an abbreviated version on subsequent pages. Numbers in the index correspond to the last two digits of the six-digit CID number.

Contents

- xi *Conference Committee*
- xiii *Optical system design reliance on technology development (Plenary Presentation)*
I. A. Neil, ScotOptix (Switzerland)
- xxxv *A perspective on the design of head-worn displays (Plenary Presentation)*
*J. Rolland, O. Cakmakci, F. Fournier, S. Vo, CREOL, The College of Optics and Photonics,
Univ. of Central Florida (United States)*

SESSION 1 OPTICAL COATINGS AND DESIGN

- 7101 02 **Progress in optical coatings (Invited Paper)** [7101-01]
A. Macleod, Thin Film Ctr., Inc. (United States)
- 7101 03 **Design principles for broadband AR coatings** [7101-02]
U. Schallenberg, mso jena GmbH (Germany)
- 7101 04 **Estimation for the number of layers of broad-band anti-reflection coatings** [7101-03]
T. Amotchkina, A. Tikhonravov, M. Trubetskov, Research Computing Ctr. (Russia)
- 7101 05 **'Gedankenspektrum' methods in optical coatings** [7101-04]
F. T. Goldstein, FTG Software Associates (United States)
- 7101 06 **Frequency filtering in optical thin film design revisited** [7101-05]
P. G. Verly, National Research Council of Canada (Canada)

SESSION 2 DEPOSITION PROCESSES

- 7101 07 **New plasma processes for antireflective structures on plastics (Invited Paper)** [7101-06]
U. Schulz, P. Munzert, Fraunhofer Institute of Applied Optics and Precision Engineering (Germany); R. Leitel, Friedrich-Schiller-Univ. (Germany); N. Bollwahn, Fraunhofer Institute of Applied Optics and Precision Engineering (Germany); I. Wendling, Friedrich-Schiller-Univ. (Germany); N. Kaiser, Fraunhofer Institute of Applied Optics and Precision Engineering (Germany); A. Tünnermann, Fraunhofer Institute of Applied Optics and Precision Engineering (Germany) and Friedrich-Schiller-Univ. (Germany)
- 7101 08 **Closed field magnetron sputtering: new generation sputtering process for optical coatings** [7101-07]
D. R. Gibson, I. Brinkley, E. M. Waddell, J. M. Walls, Applied Multilayers Ltd. (United Kingdom)
- 7101 09 **Plasma ion-assisted deposition with radio frequency powered plasma sources** [7101-08]
H. Hagedorn, M. Klosch, H. Reus, A. Zoeller, Leybold Optics GmbH (Germany)

- 7101 0B **New developments in magnetron sputter processes for precision optics (Invited Paper)** [7101-11]
M. Vergöhl, O. Werner, S. Bruns, Fraunhofer Institute for Surface Engineering and Thin Films (Germany)

SESSION 3 MONITORING

- 7101 0C **State of the art in deterministic production of optical thin films (Invited Paper)** [7101-12]
D. Ristau, H. Ehlers, S. Schlichting, Laser Zentrum Hannover e.V. (Germany); M. Lappschies, mso jena Mikroschichtoptik GmbH (Germany)
- 7101 0D **All-optical in-situ monitoring of PIAD deposition processes** [7101-13]
S. Wilbrandt, O. Stenzel, N. Kaiser, Fraunhofer IOF (Germany)
- 7101 0E **Forces in rotary motion systems** [7101-14]
M. K. Tilsch, G. K. Elliott, JDSU (United States)
- 7101 0F **A method for the determination of substrate temperature during thin film coating deposition** [7101-15]
St. Günster, H. Ehlers, D. Ristau, Laser Zentrum Hannover e.V. (Germany)
- 7101 0G **Computer simulation of coating processes with monochromatic monitoring** [7101-16]
A. Zöllner, M. Boos, H. Hagedorn, B. Romanov, Leybold Optics GmbH (Germany)

SESSION 4 FILTERS AND MANUFACTURING I

- 7101 0H **Advanced optical coatings for telecom and spectroscopic applications (Invited Paper)** [7101-17]
A. Badeen, M. Briere, P. Hook, C. Montcalm, R. Rinfret, J. Schneider, B. T. Sullivan, Iridian Spectral Technologies (Canada)
- 7101 0I **High performance notch filter coatings produced with PIAD and magnetron sputtering** [7101-18]
M. Scherer, Leybold Optics GmbH (Germany); U. Schallenberg, mso jena Mikroschichtoptik GmbH (Germany); H. Hagedorn, W. Lehnert, B. Romanov, A. Zoeller, Leybold Optics GmbH (Germany)
- 7101 0J **Sputter process with time-variant reactive gas mixture for the deposition of optical multilayer and gradient layer systems** [7101-19]
H. Bartzsch, J. Weber, K. Lau, D. GlöB, P. Frach, Fraunhofer-Institut für Elektronenstrahl- und Plasmatechnik (Germany)
- 7101 0K **Optimization and characterization of transparent photocatalytic TiO₂ thin films prepared by ion-assisted deposition** [7101-20]
R. Boughaled, S. Schlichting, H. Ehlers, D. Ristau, Laser Zentrum Hannover (Germany); I. Bannat, M. Wark, Leibniz Univ. Hannover (Germany)

- 7101 OL **Metal fluoride coatings prepared by ion-assisted deposition** [7101-21]
M. Bischoff, Friedrich-Schiller-Univ. (Germany) and Fraunhofer Institute Applied Optics and Precision Engineering (Germany); M. Sode, Friedrich-Schiller-Univ. (Germany); D. Gäbler, Fraunhofer Institute Applied Optics and Precision Engineering (Germany); H. Bernitzki, Jenoptik Laser, Optik, Systeme GmbH (Germany); C. Zaczek, Carl Zeiss SMT AG (Germany); N. Kaiser, Fraunhofer Institute Applied Optics and Precision Engineering (Germany); A. Tünnermann, Friedrich-Schiller-Univ. (Germany) and Fraunhofer Institute Applied Optics and Precision Engineering (Germany)

SESSION 5 FILTERS AND MANUFACTURING II

- 7101 OM **Toward picometer optical figuring of ultra-precision optical components using multi-aperture deposition techniques (Invited Paper)** [7101-22]
J. W. Arkwright, J. Burke, M. Gross, Commonwealth Scientific and Industrial Research Organisation (Australia)
- 7101 OO **Structural and electrical properties of low temperature deposited ITO films** [7101-25]
K. Fuchs, Friedrich-Schiller-Univ. (Germany) and Fraunhofer-Institute of Applied Optics and Precision Engineering (Germany); U. Schulz, N. Kaiser, Fraunhofer-Institute of Applied Optics and Precision Engineering (Germany); A. Tünnermann, Friedrich-Schiller-Univ. (Germany) and Fraunhofer-Institute of Applied Optics and Precision Engineering (Germany)
- 7101 OP **Reliable production of steep edge interference filters** [7101-26]
M. Lappschies, P. Pfeifer, U. Schallenberg, mso jena Mikroschichtoptik GmbH (Germany); H. Ehlers, D. Ristau, Laser Zentrum Hannover (Germany)
- 7101 OQ **Characterization of the optical properties of hydrophobic coatings and realization of high performance AR coatings with dust- and water-repellent properties** [7101-27]
S. Bruynooghe, S. Spinzig, Carl Zeiss AG (Germany); M. Fliedner, Cotec GmbH (Germany); G. J. Hsu, Carl Zeiss Sports Optics GmbH (Germany)

SESSION 6 CHARACTERISATION

- 7101 OR **Measurement of optical constants of thin films by non conventional ellipsometry, photothermal deflection spectroscopy, and plasmon resonance spectroscopy (Invited Paper)** [7101-29]
A. Krasilnikova Sytchkova, ENEA (Italy)
- 7101 OS **Determination of thermal and elastic coefficients of optical thin-film materials** [7101-30]
S. Michel, F. Lemarquis, M. Lequime, Institut Fresnel-UMR CNRS 6133, Domaine Univ. de Saint-Jérôme (France)
- 7101 OT **Measurement of thermal expansion coefficient and biaxial modulus of DWDM filters using phase-shift interferometer** [7101-31]
C.-C. Kuo, S.-H. Chen, C.-C. Lee, National Central Univ. (Taiwan)
- 7101 OU **Extraction of film interface surfaces from scanning white light interferometry** [7101-32]
D. Mansfield, Taylor Hobson Ltd. (United Kingdom)

7101 0V **Light scattering to isolate a single interface within a multilayer** [7101-33]
G. Georges, C. Deumié, C. Amra, Institut Fresnel, Domaine Univ. de Saint Jérôme (France)

7101 0W **Characterization of the optical constants of materials from the visible to the soft x-rays (Invited Paper)** [7101-34]

J. I. Larruquert, M. Fernández-Perea, M. Vidal-Dasilva, J. A. Aznárez, J. A. Méndez, Instituto de Física Aplicada - CSIC (Spain); L. Poletto, D. Garoli, Istituto Nazionale per la Fisica della Materia-CNR (Italy); A. M. Malvezzi, Univ. di Pavia (Italy) and CNISM (Italy); A. Giglia, TASC-INFN-CNR (Italy); S. Nannarone, TASC-INFN-CNR (Italy) and Univ. di Modena e Reggio Emilia (Italy)

SESSION 7 UV AND X-RAY COATINGS

7101 0X **Coatings for next generation lithography (Invited Paper)** [7101-35]
C. Zaczek, S. Müllender, H. Enkisch, Carl Zeiss SMT AG (Germany); F. Bijkerk, FOM Institute for Plasma Physics (Netherlands)

7101 0Y **Low-loss HR coatings on fused silica substrates for 193 nm micro-lithography applications** [7101-36]

S. Laux, H. Bernitzki, D. Fasold, M. Klaus, U. Schuhmann, JENOPTIK Laser, Optik, Systeme GmbH (Germany)

7101 0Z **High performance EUV and multilayer optics** [7101-37]

N. Kaiser, S. Yulin, M. Perske, T. Feigl, Fraunhofer Institute for Applied Optics and Precision Engineering (Germany)

7101 10 **Non-periodic multilayer coatings in EUV, soft x-ray and x-ray range (Invited Paper)** [7101-38]

Z. Wang, Tongji Univ. (China)

SESSION 8 APPLICATIONS

7101 12 **Optical thin films on polarization preserving cube corner retroreflectors** [7101-23]
H. Lee, Agilent Technologies, Inc. (United States)

7101 13 **Thin-film filters for a high resolution miniaturized spectrometer** [7101-41]

A. Piegari, A. K. Sytchkova, ENEA (Italy); J. Bulir, ENEA (Italy) and Institute of Physics (Czech Republic); B. Harnisch, ESA-ESTEC (Netherlands); A. Wuttig, Institute of Photonic Technology (Germany)

7101 14 **Mid-infrared filters for astronomical and remote sensing instrumentation (Invited Paper)** [7101-42]

G. Hawkins, R. Sherwood, K. Djotni, The Univ. of Reading (United Kingdom)

SESSION 9 COATINGS AND LASERS

7101 15 **Status of NIF mirror technologies for completion of the NIF facility (Invited Paper)** [7101-43]
C. J. Stolz, Lawrence Livermore National Lab. (United States)

- 7101 16 **1.5 octave dispersive dielectric multilayers for pulse compression** [7101-44]
V. Pervak, Ludwig-Maximilians-Univ. München (Germany); F. Krausz,
Ludwig-Maximilians-Univ. München (Germany) and Max-Planck-Institute of Quantum
Optics (Germany); A. Apolonski, Ludwig-Maximilians-Univ. München (Germany) and
Institute of Automation and Electrometry (Russian Federation)
- 7101 17 **Theoretical and experimental analysis of the laser irradiation parameters influence on the
LIDT of optical coatings** [7101-45]
L. Gallais, J. Capoulade, J.-Y. Natoli, M. Commandré, Institut Fresnel, CNRS, Univ. Aix
Marseille (France)
- 7101 18 **Non-destructive evaluation on optical components for high power density applications
(Invited Paper)** [7101-46]
J.-Y. Natoli, F. Wagner, A. Ciapponi, S. Palmier, L. Gallais, M. Commandré, Aix Marseille
Univ., CNRS, Institut Fresnel (France)
- 7101 19 **Design and monitoring of narrow bandpass filters composed of non-quarter-wave
thicknesses** [7101-54]
R. R. Willey, Willey Optical, Consultants (United States)

SESSION 10 INNOVATIVE CONCEPTS

- 7101 1A **Spatial dispersion of optical thin films (Invited Paper)** [7101-48]
X. Liu, Z. Luo, W. Shen, X. Sun, P. Gu, Zhejiang Univ. (China)
- 7101 1B **Resonant gratings for narrow band pass filtering applications** [7101-49]
O. Boyko, Lab. de Photonique et Nanostructures, CNRS (France); F. Lemarchand, Institut
Fresnel, CNRS, Aix-Marseille Univ., D.U. de Saint Jérôme (France); A. Talneau, Lab. de
Photonique et Nanostructures, CNRS (France); A.-L. Lehrenbach, A. Sentenac, Institut
Fresnel, CNRS, Aix-Marseille Univ., D.U. de Saint Jérôme (France)
- 7101 1C **Photochromic mesoporous hybrid coatings** [7101-50]
L. Raboin, M. Matheron, T. Gacoin, J.-P. Boilot, Lab. de Physique de la Matière Condensée,
CNRS, Ecole Polytechnique (France)
- 7101 1D **Bulk-micromachined dielectric tunable optical filter realized with inductively coupled
plasma chemical vapour deposition** [7101-51]
S. Jatta, K. Haberle, Technical Univ. Darmstadt (Germany); K. Singh, Central Electronics
Engineering Research Institute (India); B. Koegel, H. Halbritter, P. Meissner, Technische Univ.
Darmstadt (Germany)

POSTER SESSION

- 7101 1F **Reactively sputtered aluminium nitride films for spectral emission control** [7101-55]
S. Zhao, C.-G. Ribbing, Uppsala Univ. (Sweden)
- 7101 1G **Optical and structural properties of Nb_xSi_yO composite films prepared by metallic co-
sputtering process** [7101-56]
X. Cheng, Tongji Univ. (China) and Optron Co., Ltd. (Japan); B. Fan, H. Takahashi, Optron
Co., Ltd. (Japan); Z. Wang, Tongji Univ. (China)

- 7101 1H **A simple system for measuring small phase retardation of an optical thin film** [7101-57]
T. N. Hansen, H. Fabricius, DELTA Light & Optics (Denmark)
- 7101 1I **Optimizing the phase retardation caused by optical coatings** [7101-58]
H. Fabricius, T. N. Hansen, DELTA Light & Optics (Denmark)
- 7101 1J **Metal layer beamsplitters with one dielectric achromatisation layer** [7101-59]
M. Schürmann, W. Stöckl, N. Kaiser, Fraunhofer Institute Applied Optics and Precision Mechanics (Germany)
- 7101 1K **ZnS films for infrared optical coatings: improvement of adhesion to Ge substrates** [7101-60]
M. Sánchez-Agudo, I. Génova, C.I.D.A.-I.T.M. (Spain); H. J. B. Orr, Thin Film Solutions Ltd. (United Kingdom); G. Harris, Univ. of Dundee (United Kingdom); G. Pérez, C.I.D.A.-I.T.M. (Spain)
- 7101 1L **Next generation end hall ion source in the optical thin film production process** [7101-61]
H. Niederwald, Carl Zeiss AG (Germany); L. Mahoney, Veeco Instruments Inc. (United States)
- 7101 1N **Fabrication of far infrared rib waveguides based on Te-Ge-Ga films deposited by co-thermal evaporation** [7101-65]
S. Albert, E. Barthelemy, C. Vigreux, A. Pradel, Institut Charles Gerhardt (France); M. Barillot, Thales Alenia Space (France)
- 7101 1O **Synthesis and study of structure and nonlinear optical properties of silicon carbide nanocrystal films** [7101-66]
A. Borshch, M. Brodyn, V. Volkov, V. Lyakhovetski, V. Rudenko, Institute of Physics (Ukraine); A. Semenov, V. Pusikov, Institute of Monocrystals (Ukraine)
- 7101 1Q **AZO films prepared by r.f. magnetron sputtering: structural, electrical, and optical properties** [7101-68]
M. L. Grilli, A. Krasilnikova Sytchkova, ENEA (Italy); S. Boycheva, Technical Univ. of Sofia (Bulgaria); A. Piegari, ENEA (Italy)
- 7101 1R **Laser induced fluorescence and absorption measurements for DUV optical thin film characterization** [7101-69]
Ch. Mühlig, W. Triebel, S. Kufert, S. Bublitz, Institute of Photonic Technology (Germany)
- 7101 1S **Nonlinear refraction of gold island films** [7101-71]
A. Borshch, M. Brodyn, R. Fedorovych, V. Liakhovetskyi, V. Volkov, Institute of Physics (Ukraine)
- 7101 1U **Metrology in the soft x-ray range: from EUV to the water window** [7101-73]
C. Laubis, F. Scholze, G. Ulm, Physikalisch-Technische Bundesanstalt (Germany)
- 7101 1V **Comparison of measured and calculated performance of a 7-channel astronomical instrument** [7101-74]
St. Günster, D. Ristau, Laser Zentrum Hannover e.V. (Germany); J. Greiner, Max-Planck-Institut für extraterrestrische Physik (Germany); C. Tafelmaier, Tafelmaier Dünnschicht Technik GmbH (Germany)

- 7101 1X **Modification of optical properties of metal island films by electric field-assisted dissolution of clusters** [7101-76]
J. Sancho-Parramon, V. Janicki, H. Zorc, M. Lončarić, Ruđer Bošković Institute (Croatia)
- 7101 1Y **Development of a hybrid monitoring strategy to the deposition of chirped mirrors by plasma-ion assisted electron evaporation** [7101-77]
O. Stenzel, S. Wilbrandt, N. Kaiser, Fraunhofer IOF (Germany); D. Fasold, JENOPTIK Laser, Optik, Systeme GmbH (Germany)
- 7101 20 **An in-situ investigation of the surface oxidation of ultra-thin films of Ni and Hf** [7101-79]
S. Song, F. Placido, Univ. of the West of Scotland (United Kingdom)

Author Index

Conference Committee

Symposium Chair

David M. Williamson, West Malvern (United Kingdom); NRCA Fellow,
Nikon Research Corporation of America (USA)

Symposium Co-Chairs

Andreas Tünnermann, Fraunhofer-Institut für Angewandte Optik und
Feinmechanik (Germany)

Jean-Louis Meyzonnette, Institut d'Optique, Ecole Supérieure
d'Optique (France)

Conference Chairs

Norbert Kaiser, Fraunhofer-Institut für Angewandte Optik und
Feinmechanik (Germany)

Michel Lequime, Institut Fresnel (France)

H. Angus Macleod, Thin Film Center, Inc. (United States)

Program Committee

Claude Amra, Institut Fresnel (France)

Salvador Bosch Puig, Universidad de Barcelona (Spain)

Bertrand G. Bovard, Teledyne Scientific Company (United States)

Mireille Commandré, Institut Fresnel (France)

Angela Duparré, Fraunhofer-Institut für Angewandte Optik und
Feinmechanik (Germany)

Keith L. Lewis, Electromagnetic Remote Sensing Defence Technology
Center (United Kingdom)

Xu Liu, Zhejiang University (China)

Ludvik Martinu, École Polytechnique de Montréal (Canada)

Angela M. Piegari, ENEA (Italy)

Guillaume L. Ravel, CEA LITEN (France)

Carl Gustaf Ribbing, Uppsala University (Sweden)

Detlev Ristau, Laser Zentrum Hannover e.V. (Germany)

Ulrike Schulz, Fraunhofer-Institut für Angewandte Optik und
Feinmechanik (Germany)

Christopher J. Stolz, Lawrence Livermore National Laboratory (United
States)

Hrvoje Zorc, Institut Ruđer Bošković (Croatia)

Session Chairs

- 1 Optical Coatings and Design
Angela M. Piegari, ENEA (Italy)
Brian T. Sullivan, Iridian Spectral Technologies (Canada)
- 2 Deposition Processes
Ludvik Martinu, Ecole Polytechnique de Montréal (Canada)
Mikko Ritala, University of Helsinki (Finland)
- 3 Monitoring
Anna Krasilnikova Sytchkova, ENEA (Italy)
Christoph Zaczek, Carl Zeiss SMT AG (Germany)
- 4 Filters and Manufacturing I
Mireille Commandré, Institut Fresnel (France)
Salvador Bosch Puig, Universidad de Barcelona (Spain)
- 5 Filters and Manufacturing II
H. Angus Macleod, Thin Film Center, Inc. (United States)
Christopher J. Stolz, Lawrence Livermore National Laboratory (United States)
- 6 Characterisation
Gary J. Hawkins, University of Reading (United Kingdom)
Norbert Kaiser, Fraunhofer-Institut für Angewandte Optik und
Feinmechanik (Germany)
- 7 UV and X-ray Coatings
Hrvoje Zorc, Institut Ruder Boškovic (Croatia)
Xu Liu, Zhejiang University (China)
- 8 Applications
Ulrike Schulz, Fraunhofer-Institut für Angewandte Optik und
Feinmechanik (Germany)
Carl G. Ribbing, Uppsala University (Sweden)
- 9 Coatings and Lasers
Claude Amra, Institut Fresnel (France)
Detlev Ristau, Laser Zentrum Hannover e.V. (Germany)
- 10 Innovative Concepts
John W. Arkwright, Commonwealth Scientific and Industrial Research
Organisation (Australia)
Michel Lequime, Institut Fresnel (France)

Optical system design reliance on technology development

Iain A. Neil

ScotOptix

Via Miravalle 25A, CH-6900 Massagno, Switzerland

++41 (0)91 950 0158 (voice & fax)

++41 (0)79 398 5524 (mobile)

scotoptix@aol.com



WELCOME

**Firstly, thanks goes to SPIE,
the organizing committee, Chairs
and Co-Chairs of the Conference
for acceptance of this presentation**



INTRODUCTION

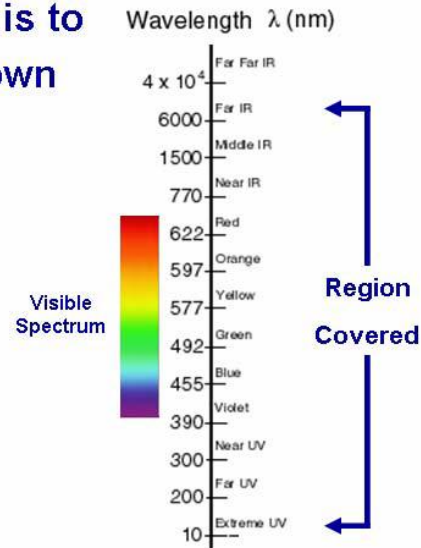
Before commencing with an outline of the presentation an explanation of the the definitions used throughout is given

DEFINITIONS

- ① **Technology development is the progression over time of manufactured optical components:**
 - **Materials \approx optical substrates**
 - **Coatings \approx multi-layer thin films**
 - **Surfaces \approx optical surface profiles**
- ② **Optical design software is a tool to apply technology**
- ③ **Optical designer ‘creates’ the optics portion of the of the optical system design utilizing optical design software to apply technology**
- ④ **FOV is Field of View & NA is Numerical Aperture**

DEFINITIONS (Cont'd)

- ⑤ Object is to the left and Image is to the right unless otherwise shown
- ⑥ Three wavebands discussed:
 - Infrared $\approx 0.7\text{-}1.5, 3\text{-}5$ & $8\text{-}13\mu\text{m}$
(700-1500, 3000-5000 & 8000-13000nm)
 - Visible $\approx 0.435\text{-}0.656\mu\text{m}$
(435-656nm)
 - Ultraviolet $\approx 0.434\text{-}0.013\mu\text{m}$
(434.4-13.4nm)



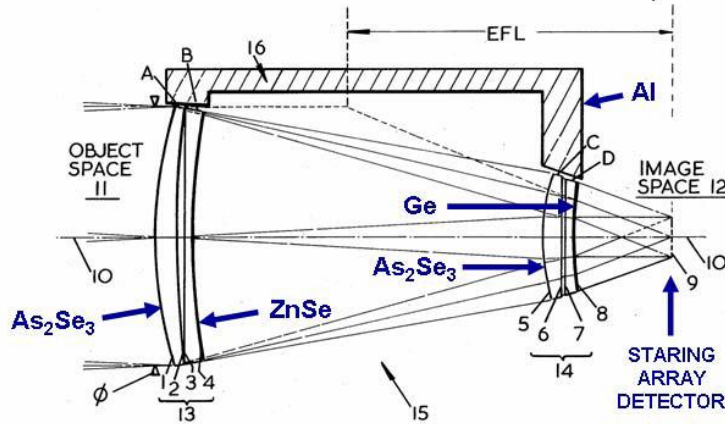
OUTLINE

- By way of mainly the US Patent database, examples are given to illustrate the reliance of optical system design on key technology
- The examples are categorized by waveband of operation and partly chronologically
- Performance characteristics are not discussed but all examples may be considered high performance for their intended applications

WAVEBAND 1 INFRARED

EXAMPLE 1.1 PETZVAL OBJECTIVE – SECURITY

Passively Athermalized System
EFL=51mm F/1.5 FOV \varnothing =5° Waveband=8-13 μ m

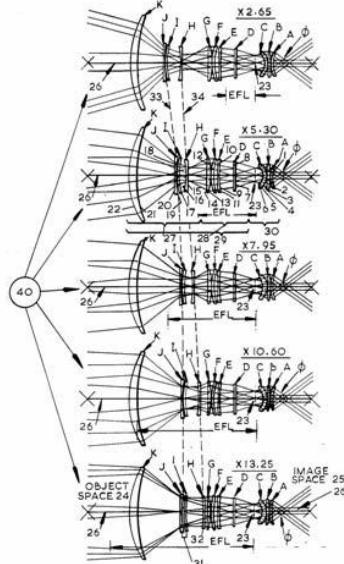


US Pat. No. 4,505,535 A1 I.A.Neil Mar. 19, 1985

KEY TECHNOLOGY	
✓	MATERIAL
	COATING
	SURFACE
BENEFITS	
	SOLID STATE
	ROBUST
ISSUES	
	TOXIC MATERIAL
	MATERIAL QUALITY

EXAMPLE 1.2a

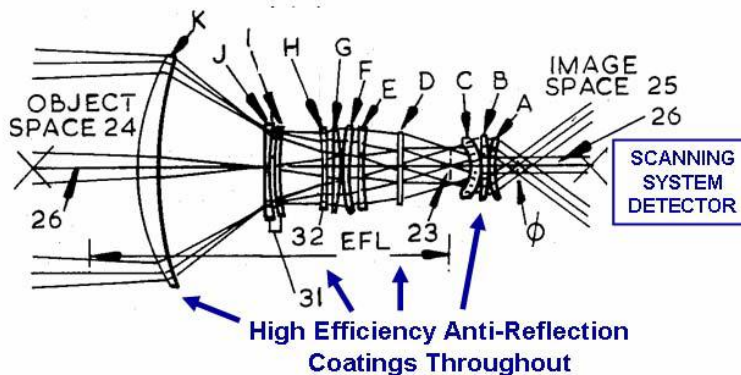
ZOOM TELESCOPE – SECURITY



EXAMPLE 1.2b

ZOOM TELESCOPE – SECURITY

Compact Mechanically Compensated Zoom System
Zoom Ratio=5x Exit Pupil $\phi=10\text{mm}$ & $\text{FOV}\phi=72^\circ$ Waveband=8-13 μm

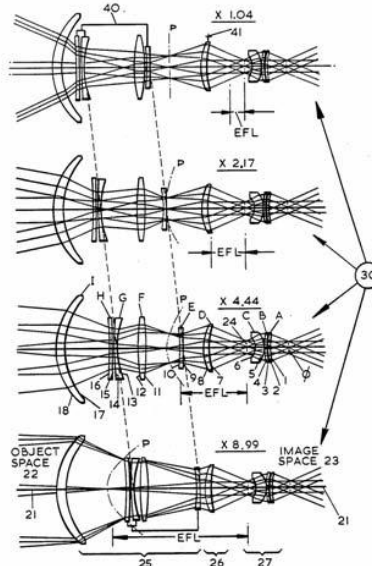


KEY TECHNOLOGY	
	MATERIAL
✓	COATING
	SURFACE
BENEFITS	
COMPACT	
ISSUES	
NONE	

US Pat. No. US4,659,171 A1 I.A.Neil Apr. 21, 1987

EXAMPLE 1.3a

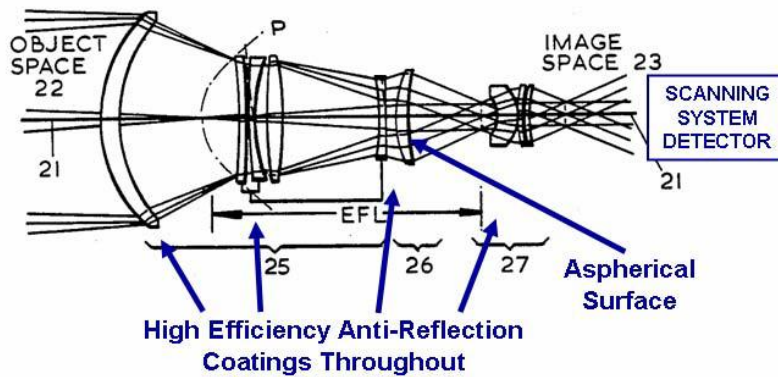
ZOOM TELESCOPE – SECURITY



EXAMPLE 1.3b

ZOOM TELESCOPE – SECURITY

Compact Optically Compensated Zoom System
Zoom Ratio=9x Exit Pupil \varnothing =14.4mm & FOV \varnothing =60° Waveband=8-13 μ m

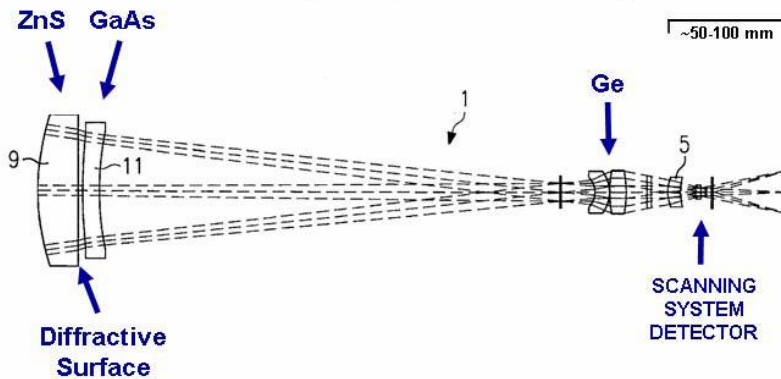


US Pat. No. 4,632,498 A1 I.A.Neil Dec. 30, 1986

KEY TECHNOLOGY	
	MATERIAL
✓	COATING
✓	SURFACE
BENEFITS	
COMPACT	
SIMPLE MECHANICS	
ISSUES	
FOCUS DRIFT THROUGH ZOOM	
ASPHERE COST	

EXAMPLE 1.4 OBJECTIVE – SECURITY

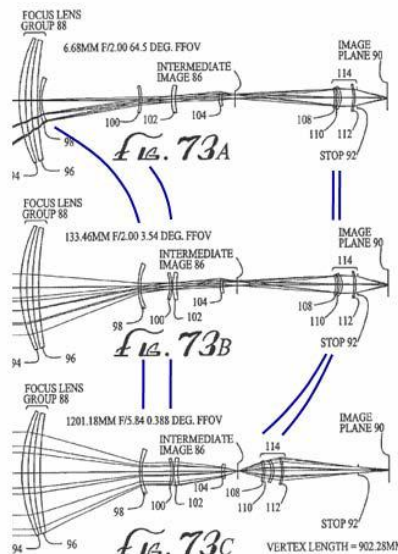
Passively Athermalized & Color Corrected Air Spaced Doublet
with Diffractive Surface
Waveband=8-13 μ m (possibly 3-5 μ m depending on materials)



US Pat. No. 5,504,628 A1 J.F.Borchard Apr. 2, 1996

KEY TECHNOLOGY	
✓	MATERIAL
	COATING
✓	SURFACE
BENEFITS	
	SOLID STATE
	ROBUST
ISSUES	
	SECONDARY COLOR
	LONG LENGTH

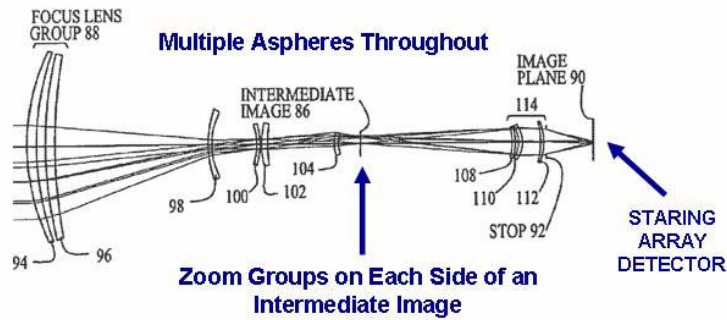
EXAMPLE 1.5a ZOOM OBJECTIVE – SECURITY



EXAMPLE 1.5b

ZOOM OBJECTIVE – SECURITY

Compound Zoom System
 Zoom Ratio=180x EFL=6.7-1201mm F/2-5.84 FOV \varnothing =64.5-0.4°
 Wavebands=3-5 μ m or 8-13 μ m



KEY TECHNOLOGY	
	MATERIAL
✓	COATING
✓	SURFACE
BENEFITS	
	HIGH ZOOM RATIO
ISSUES	
	COMPLEX MECHANICS
	IMAGE F/NO VARIES
	ASPHERE COST

US Pat. No. 7,224,535 B2 I.A.Neil May 29, 2007

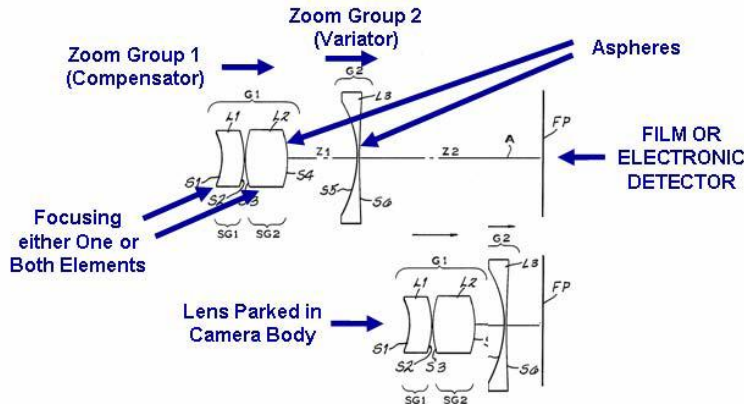
WAVEBAND 2

VISIBLE

EXAMPLE 2.1

COMPACT CAMERA ZOOM OBJECTIVE – PHOTOGRAPHIC CONSUMER

Zoom Objective System with 2x Zoom Ratio
EFL=35.7-68.5mm F/3.5-6.8 ImageØ=43.2mm Waveband=Visible



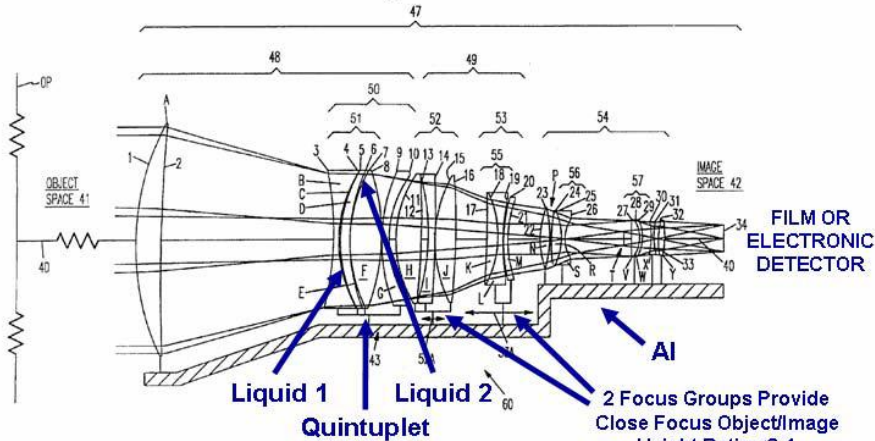
US Pat. No. 4,936,661 A1 E.I.Betensky, M.H.Kreitzer & J.Moskovich Jun. 26, 1990

KEY TECHNOLOGY	
	MATERIAL
	COATING
✓	SURFACE
BENEFITS	
	SIMPLE
	COMPACT
	LOW COST
ISSUES	
	MOLDED ASPHERES

EXAMPLE 2.2a

TELEPHOTO OBJECTIVE – PHOTOGRAPHIC CINE

Passively Athermalized & Color Corrected System with Liquid Elements
EFL=693mm F/2.75 ImageØ=28.9mm Waveband=435-656nm

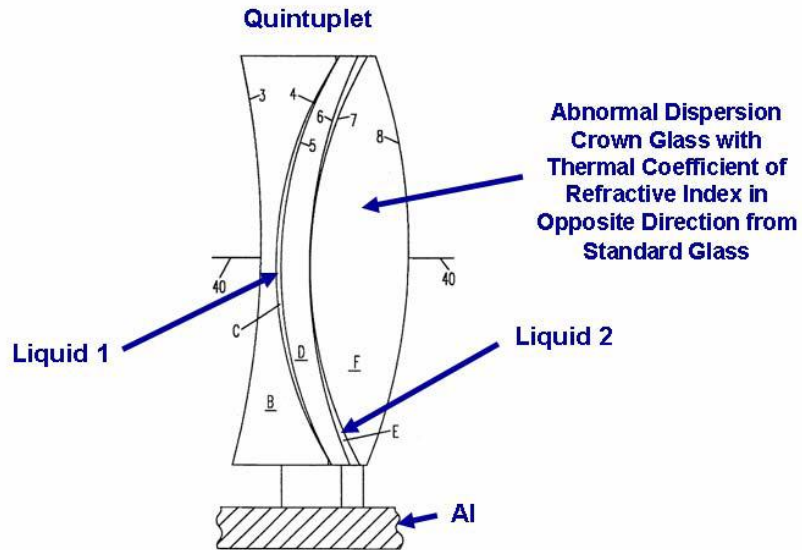


US Pat. No. 5,638,215 A1 I.A.Neil Jun. 10, 1997

KEY TECHNOLOGY	
✓	MATERIAL
✓	COATING
	SURFACE
BENEFITS	
	LOW COST GLASSES
	COMPACT
ISSUES	
	LIQUID DISCOLORATION
	LOW TEMPERATURE

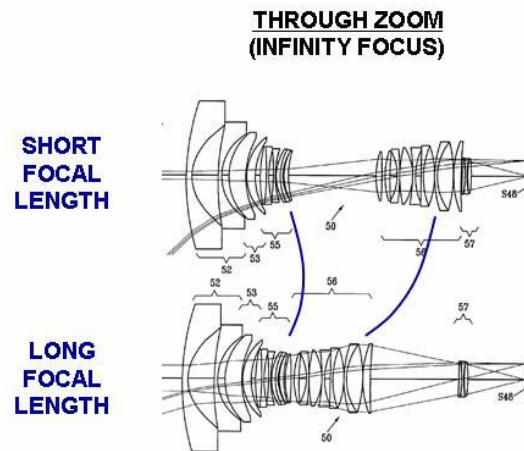
EXAMPLE 2.2b

TELEPHOTO OBJECTIVE – PHOTOGRAPHIC CINE



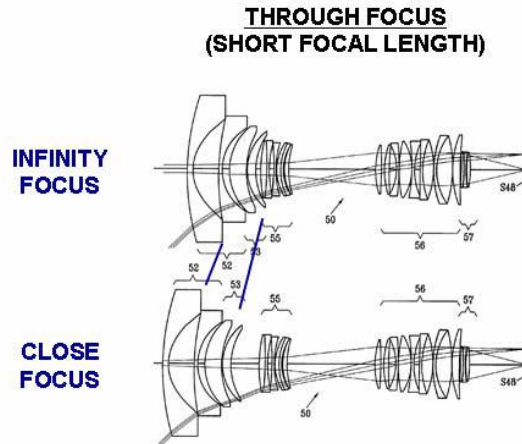
EXAMPLE 2.3a

MACRO FOCUS ZOOM OBJECTIVE – PHOTOGRAPHIC CINE



EXAMPLE 2.3b

MACRO FOCUS ZOOM OBJECTIVE – PHOTOGRAPHIC CINE

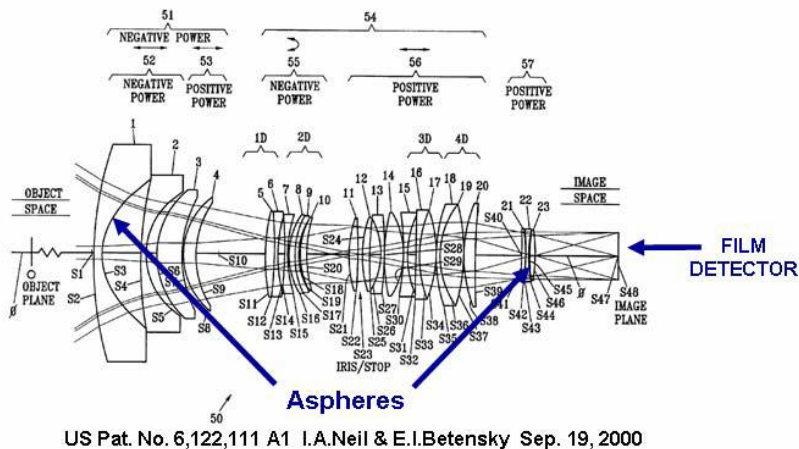


Close Focus Object/Image Height Ratio = 2.5:1 (At Long Focal Length)

EXAMPLE 2.3c

ZOOM OBJECTIVE – PHOTOGRAPHIC CINE

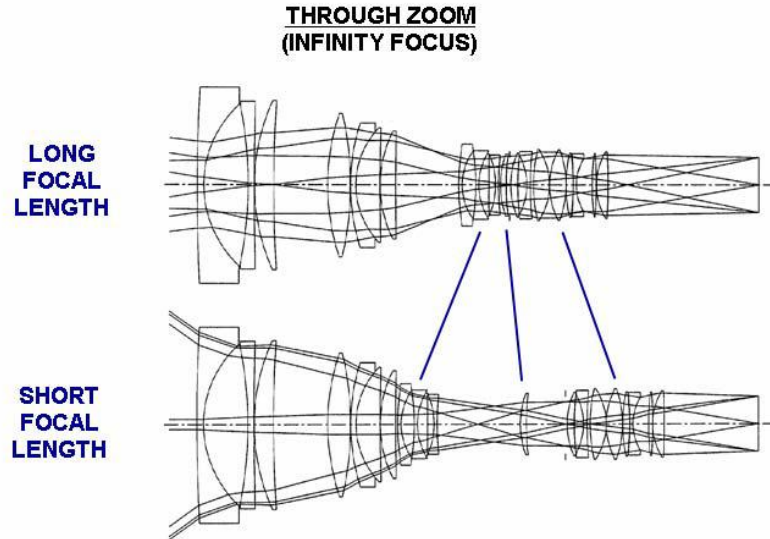
Macro Focus Zoom System with 3.5x Zoom Ratio
EFL=14.5-50mm F/2.2 ImageØ=28.9mm Waveband=455-644nm



KEY TECHNOLOGY	
	MATERIAL
✓	COATING
✓	SURFACE
BENEFITS	
	VERSATILE
	FIXED FOCAL LENGTH OPTION
ISSUES	
	COMPLEX MECHANICS
	ASPHERE COST

EXAMPLE 2.4a

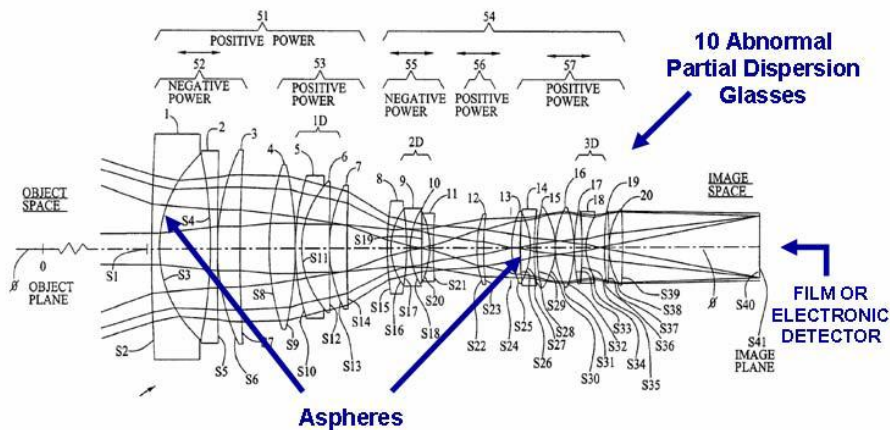
ZOOM OBJECTIVE – PHOTOGRAPHIC CINE



EXAMPLE 2.4b

ZOOM OBJECTIVE – PHOTOGRAPHIC CINE

Compact Zoom Objective System with 4.7x Zoom Ratio
EFL=19-90mm F/2.7 ImageØ=27.8mm Waveband=455-644nm



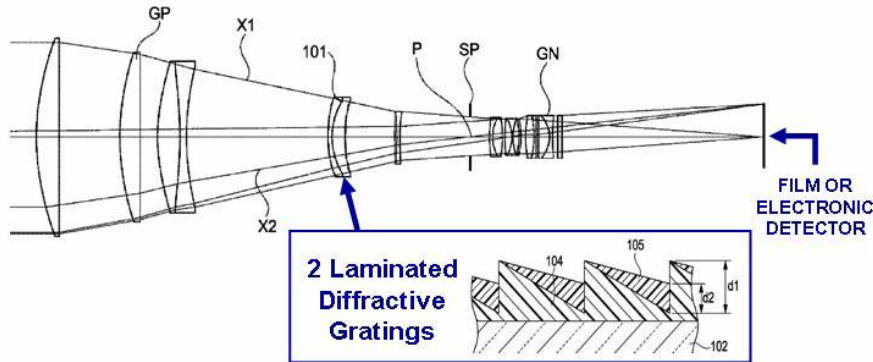
US Pat. No. 7,123,421 B1 J.Moskovich, I.A.Neil & T.Yamanashi Oct. 17, 2006

KEY TECHNOLOGY	
✓	MATERIAL
✓	COATING
✓	SURFACE
BENEFITS	
COMPACT	
VERSATILE	
FIXED FOCAL LENGTH OPTION	
ISSUES	
COMPLEX MECHANICS	
ASPHERE COST	

EXAMPLE 2.5

OBJECTIVE – PHOTOGRAPHIC PROSUMER

Telephoto System with Diffractive Surface
 EFL=780mm F/5.8 ImageØ=43.2mm Waveband=435-656nm



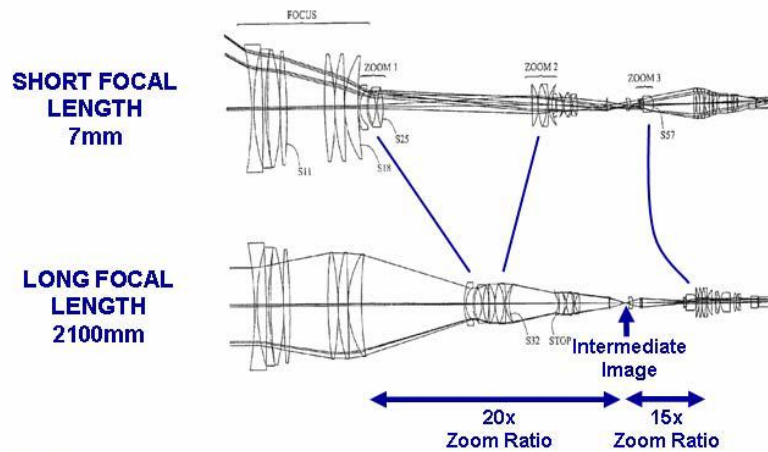
KEY TECHNOLOGY	
✓	MATERIAL
	COATING
✓	SURFACE
BENEFITS	
	COMPACT
	COLOR CORRECTED
	REDUCED NO. OF EXOTIC GLASSES
ISSUES	
	FLARE

US Pat. Pub. No. 2008/0088950 A1 H.Endo Apr. 17, 2008

EXAMPLE 2.6a

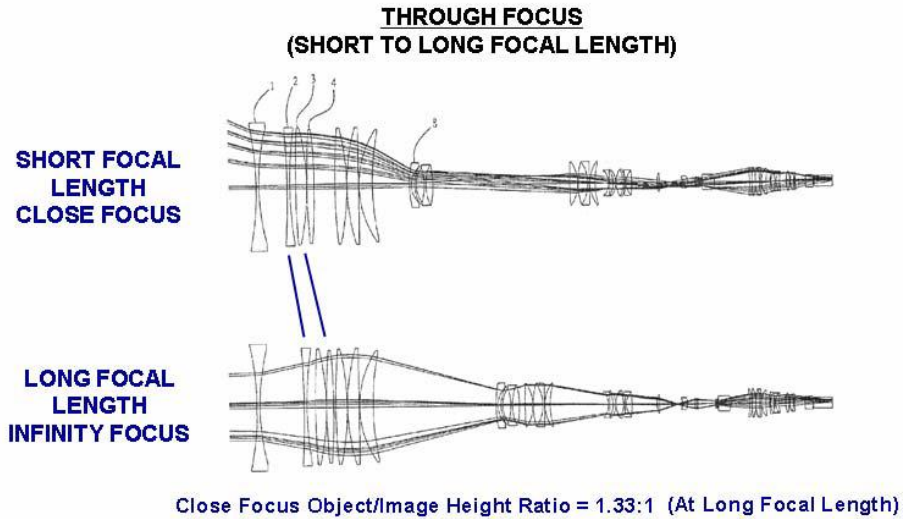
ZOOM OBJECTIVE – PHOTOGRAPHIC HDTV

**THROUGH ZOOM
(INFINITY FOCUS)**



EXAMPLE 2.6b

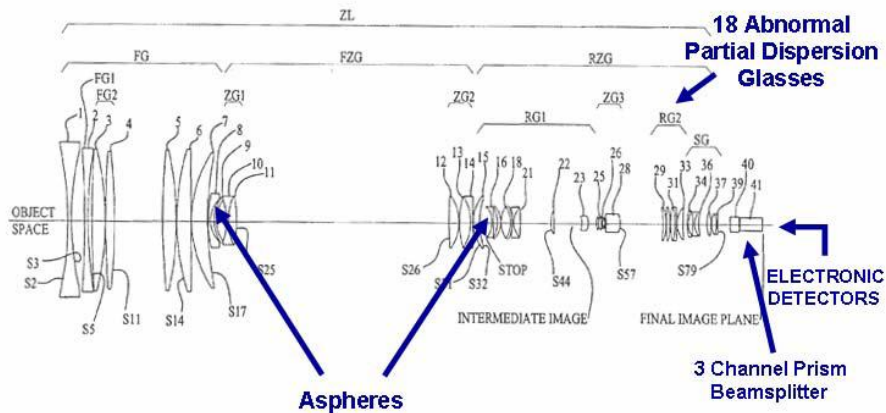
ZOOM OBJECTIVE – PHOTOGRAPHIC HDTV



EXAMPLE 2.6c

ZOOM OBJECTIVE – PHOTOGRAPHIC HDTV

Compound Zoom System with 300x Zoom Ratio
EFL=7-2100mm F/2-13 ImageØ=11mm Waveband=Visible



KEY TECHNOLOGY	
✓	MATERIAL
✓	COATING
✓	SURFACE
BENEFITS	
	LARGE ZOOM RATIO
	VERSATILE
ISSUES	
	COMPLEX MECHANICS
	ASPHERE COST

US Pat. No. 6,691,188 B2 E.I.Betensky, J.B.Caldwell, I.A.Neil & T.Yamanashi Nov. 1, 2005

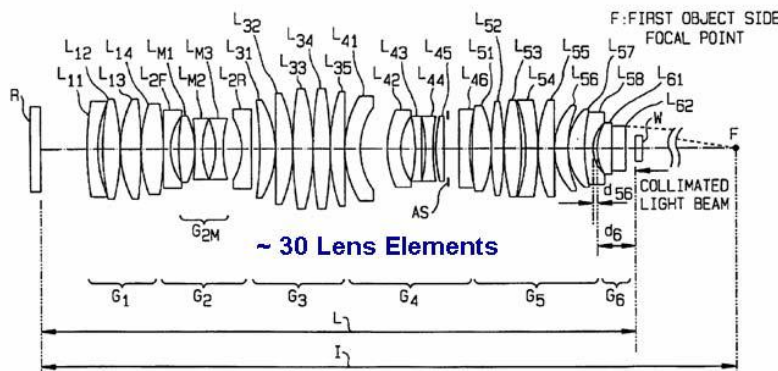
WAVEBAND 3 ULTRAVIOLET

EXAMPLE 3.1

PROJECTION RELAY LENS – MICROLITHOGRAPHIC

All Refractive Projection System

RELAY=5:1 NA=0.57 ImageØ=31.2mm Wavelengths=193, 248 & 365nm



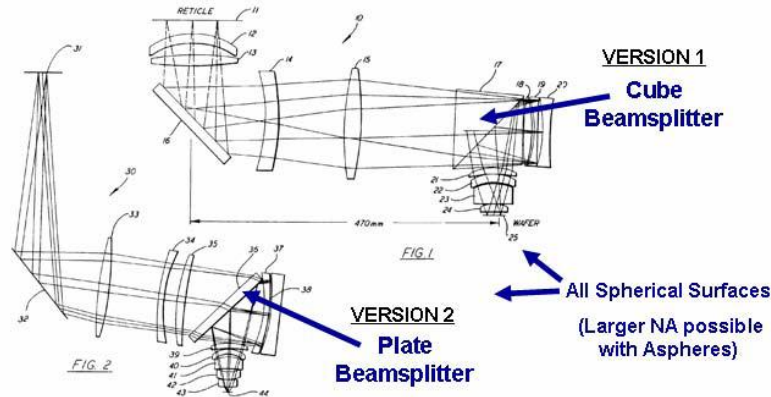
KEY TECHNOLOGY	
	MATERIAL
✓	COATING
✓	SURFACE
BENEFITS	
	RESOLUTION
ISSUES	
	INHOMOGENEITY & BIREFRINGENCE
	SURFACE QUALITY
	ALIGNMENT

US Reissued Pat. No. RE 37,846E H.Matsuzawa, M.Kobayashi, K.Endo & Y.Suenaga Sep. 17, 2002

EXAMPLE 3.2

PROJECTION RELAY LENS – MICROLITHOGRAPHIC

Refractive/Reflective Projection System
 RELAY=4:1 NA=0.45 ImageØ=30mm Wavelengths=240-256nm



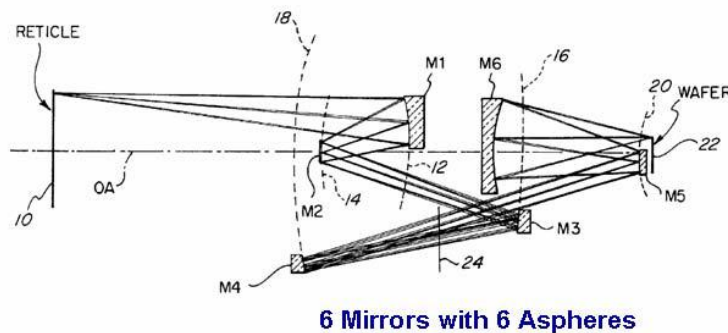
KEY TECHNOLOGY	
✓	MATERIAL
✓	COATING
	SURFACE
BENEFITS	
	RESOLUTION
ISSUES	
	ALIGNMENT

US Pat. No. 4,953,960 A1 D.M.Williamson Sep. 4, 1990

EXAMPLE 3.3

PROJECTION RELAY OPTICS – MICROLITHOGRAPHIC

All Reflective Projection System
 RELAY=4:1 NA=0.25 ImageØ=31mm Wavelengths=13.4nm & <200nm



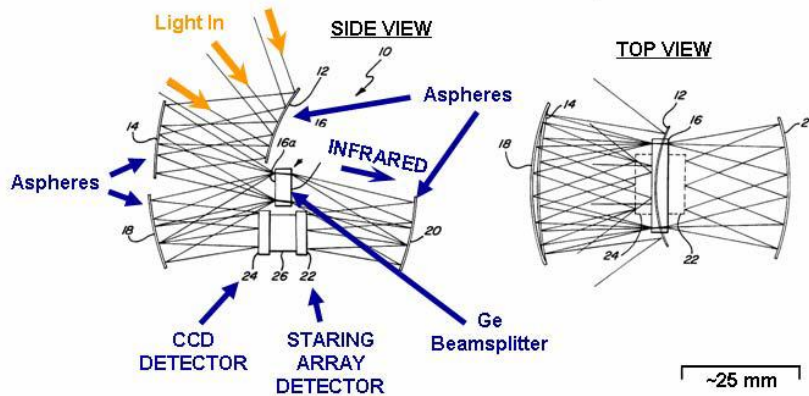
KEY TECHNOLOGY	
	MATERIAL
✓	COATING
✓	SURFACE
BENEFITS	
	HIGH RESOLUTION
ISSUES	
	@13.4nm <10% TRANSMISSION WITH COATINGS
	ASPHERE COST
	ALIGNMENT

US Pat. No. 5,815,310 A1 D.M.Williamson Sep. 29, 1998

WAVEBAND 4 MULTIPLE

EXAMPLE 4.1 OBJECTIVE – SECURITY

Dual Waveband System
 F/4.5(elev), F/1.5(azim) & F/2.3(average) FOV \varnothing =40°(elev.) & 53°(azim.)
 Wavebands=Visible & 8-13 μ m



KEY TECHNOLOGY	
	MATERIAL
✓	COATING
✓	SURFACE
BENEFITS	
	COMPACT
	SOLID STATE
	ROBUST
ISSUES	
	ASPHERE COST

US Pat. No. 5,847,879 A1 L.G.Cook Dec. 8, 1998

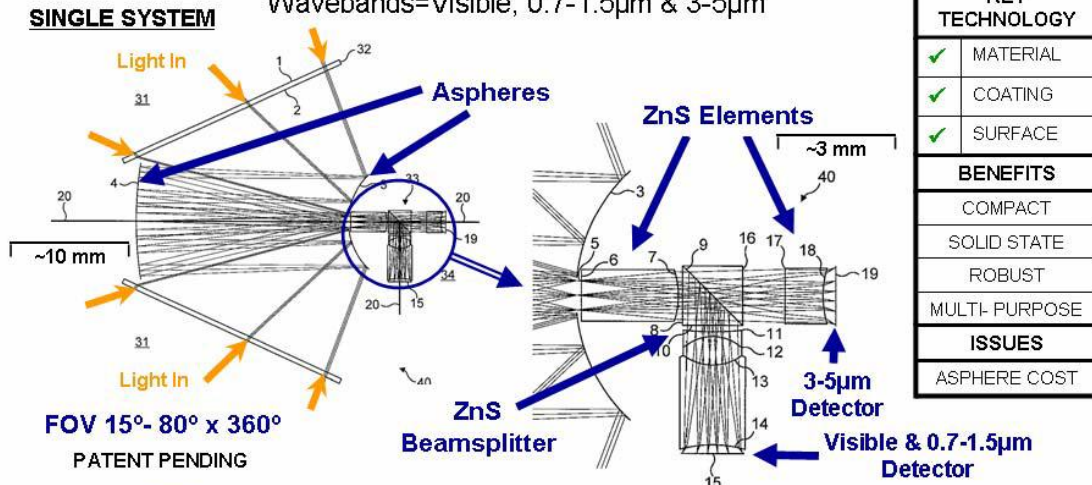
EXAMPLE 4.2a

OBJECTIVE – SURVEILLANCE

Compact Multi-waveband Wide Angle Objective

FOV 15°- 80° x 360°

Wavebands=Visible, 0.7-1.5µm & 3-5µm



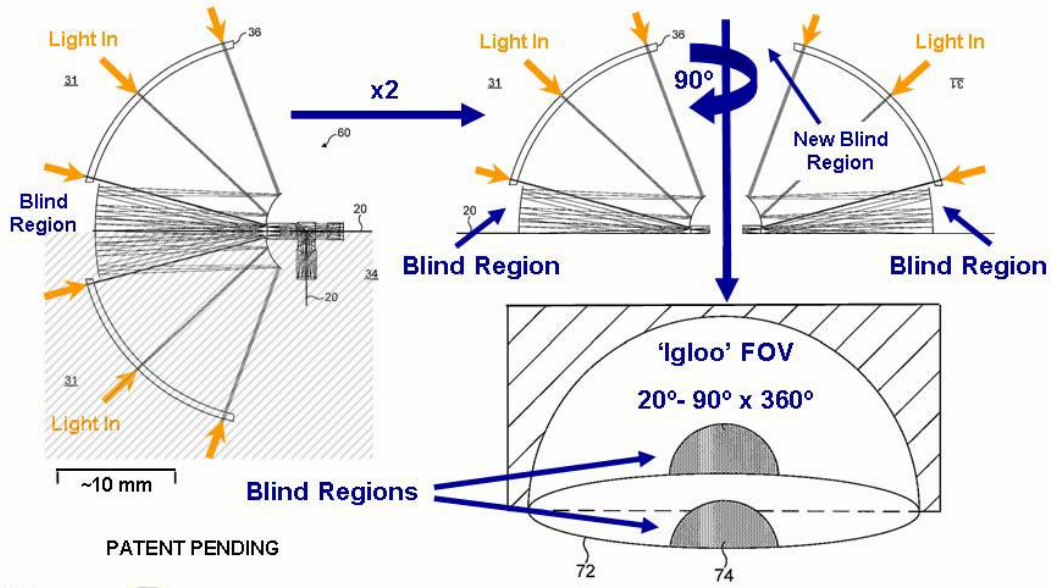
SPIE Europe
Optical Systems Design

Glasgow, Scotland, United Kingdom – 2nd September 2008

35

EXAMPLE 4.2b

OBJECTIVE – SURVEILLANCE



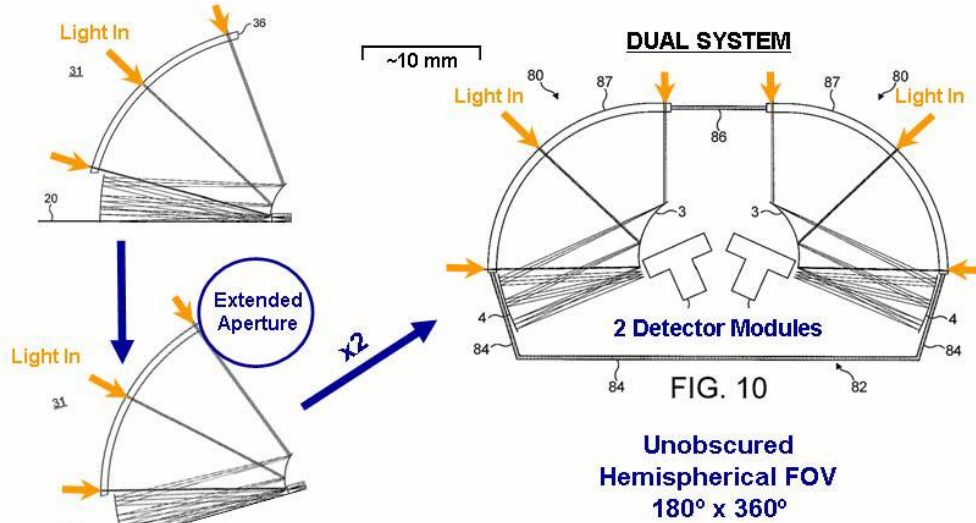
SPIE Europe
Optical Systems Design

Glasgow, Scotland, United Kingdom – 2nd September 2008

36

EXAMPLE 4.2c

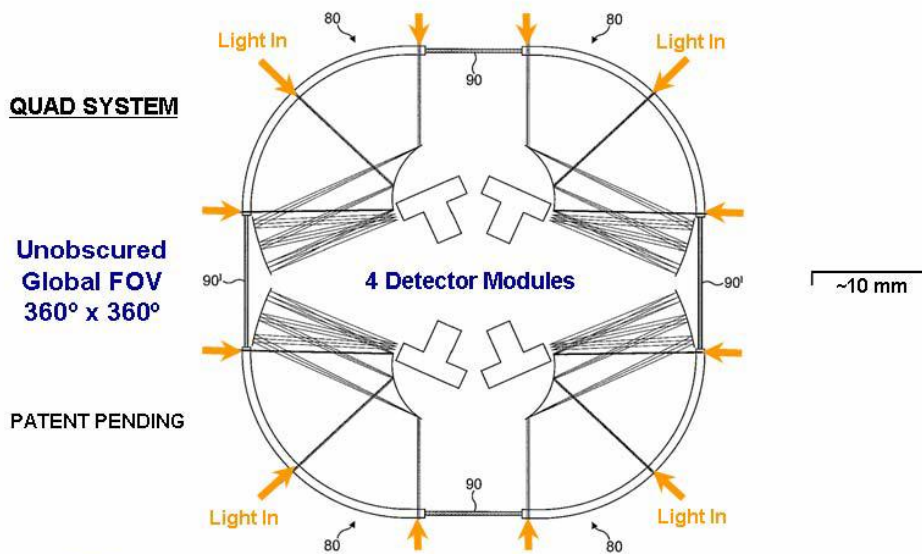
OBJECTIVE – SURVEILLANCE



PATENT PENDING

EXAMPLE 4.2d

OBJECTIVE – SURVEILLANCE



PATENT PENDING

KEY TECHNOLOGY SUMMARY

EXAMPLE	WAVE BAND															
	INFRARED					VISIBLE						ULTRAVIOLET			MULTI	
	1.1	1.2	1.3	1.4	1.5	2.1	2.2	2.3	2.4	2.5	2.6	3.1	3.2	3.3	4.1	4.2
CIRCA	80's	80's	80's	90's	00's	90's	90's	00's	00's	00's	00's	90's	90's	90's	90's	00's
MATERIAL	✓			✓			✓		✓	✓	✓		✓			✓
COATING		✓	✓		✓		✓	✓	✓		✓	✓	✓	✓	✓	✓
SURFACE			✓	✓	✓	✓		✓	✓	✓	✓	✓		✓	✓	✓

CONCLUSION

- Usually technology provides 'improvements' but occasionally it is 'disruptive' in that it dramatically changes the optical system design such as enabling a new form of design
- In the specific case of disruptive technology this usually appears to happen separately in either materials, coatings or surfaces
- No apparent trend in technology development except:

"Necessity is the mother of invention"

Plato c. 400 BC

ACKNOWLEDGEMENTS

**Thanks goes to the following individuals
for contributions to this presentation**

David W. Samuelson

David M. Williamson

Andy Wood



A Perspective on the Design of Head-Worn Displays

Jannick Rolland with

Ozan Cakmakci, Florian Fournier, and Sophie Vo

CREOL, The College of Optics and Photonics
the University of Central Florida

<http://odalab.ucf.edu>
jannick@odalab.ucf.edu



Highlights

Introduction

Applications

Prior Work

Early work at ODALab

Current Technologies under Development

Head-mounted Projection Displays (HMPD)

Eyeglass Head-Worn Displays (HWD)

Why Head-Worn Displays?

Assuming HWDs can be designed aesthetically (which is not a given) to meet with social acceptance:

- **Mobility**

- **Privacy**



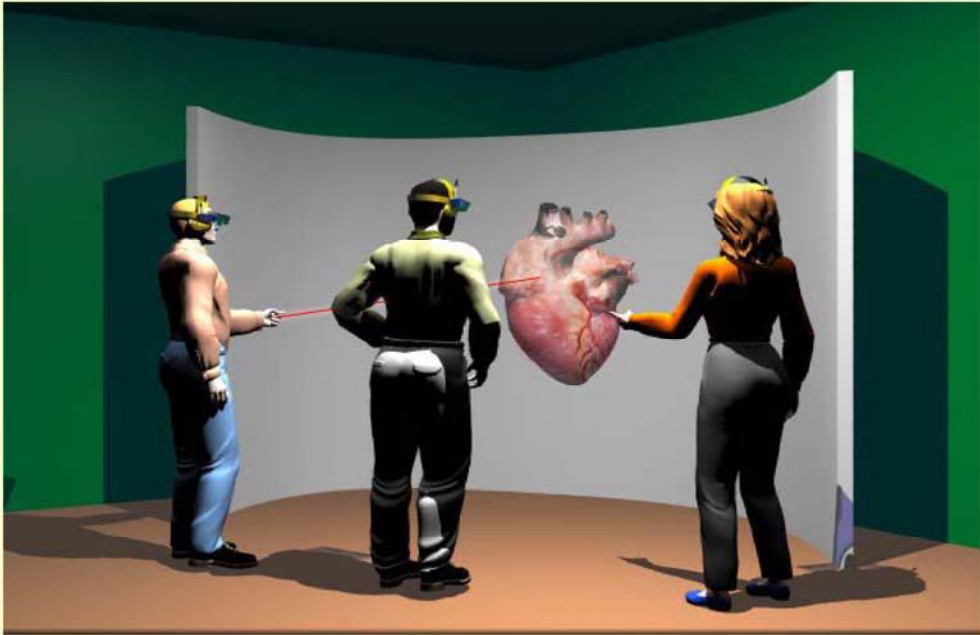
- **Constancy:** Provides the basis for novel user interfaces that are available constantly (on a demand basis) to the user

Science Fiction Sets Expectations of Where we Aim to Be Going!



* Goldsman, A. (1998). Lost in Space. New Line Cinema

Medical Rooms of the Future



Telemedicine: Face to Face Teleportal



Fig 1. Vision of “see-thru-my-eyes” capability. (1) Doctor in local control room guides (2) remote treatment via stereoscopic see-thru headset worn by emergency technician.



Fig.2. Vision of mobile “Face-to-Face” interaction (1) remote team member wearing 3D face recording system talk in to (2) team leader in control center.

Courtesy of Frank Biocca, MSU



Wearable Displays: **A Range of Possibilities**

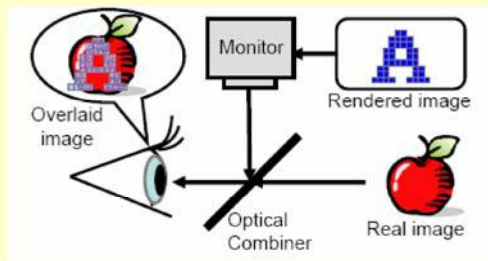
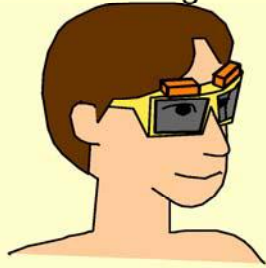
Their future lies in large part in their “seamless” integration with tangible interfaces around us

**Augmented Reality
/ Mixed Reality
Vs. Virtual Reality (full immersion)**

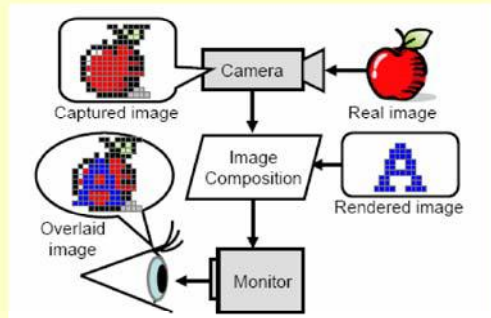
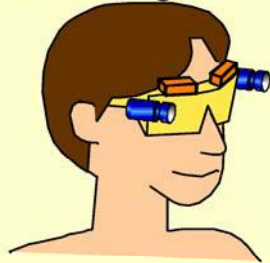


Augmented/Mixed Reality

Optical See-through

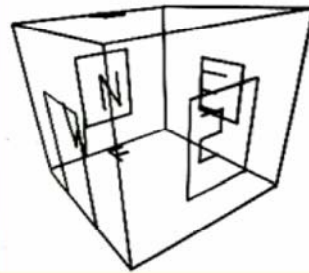


Video See-through



Historical Notes

First graphics-driven HWD was developed by Ivan Sutherland in the 1960s.



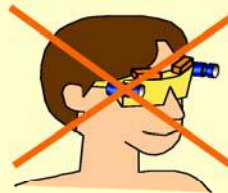
Augmented Reality Displays

Early (first?) stereoscopic VST-HMD

- HMD-mounted stereo cameras with custom-designed lenses compensate for display distortion (Biocca & Rolland, Presence 1998)



Some applications call for
optical see-through
capability



Highlights from Past Development

- U.S. Army first to fly a helmet-mounted sighting system on the Cobra helicopter.
- IHADSS (Integrated Helmet and Display Sighting System) was then deployed by the U.S. Army for the AH-64 Apache Helicopter.

IHADSS, while monocular, greatly contributed to the proliferation of all types of HMDs.

The success of HWD design is most likely to occur when developed

- In the context of the users and
- Targeted at specific applications

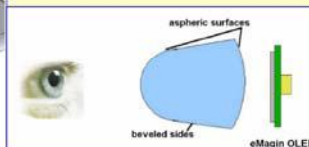
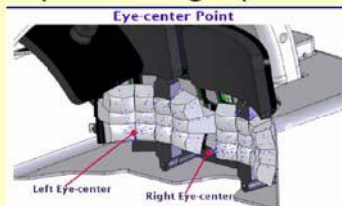
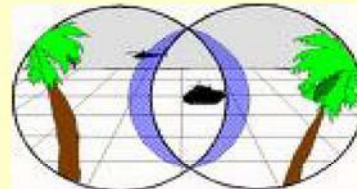
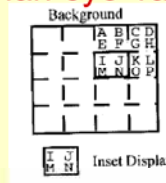
A Main Design Trade-off

FOV vs. Resolution - Currently limited by microdisplays

Angle subtended by a pixel = $\frac{FOV}{\# \text{ of pixels}}$ **Human eye 1 arcmin**

Approaches:

- 1) High-resolution area of interest or inset
- 2) Partial binocular overlap (“Luning”)
- 3) Optical tiling (Kaiser, Sensics)



Recent developments by Sensics.

Driven by Medical Visualization: VRDA Tool “Virtual Reality Dynamic Anatomy”

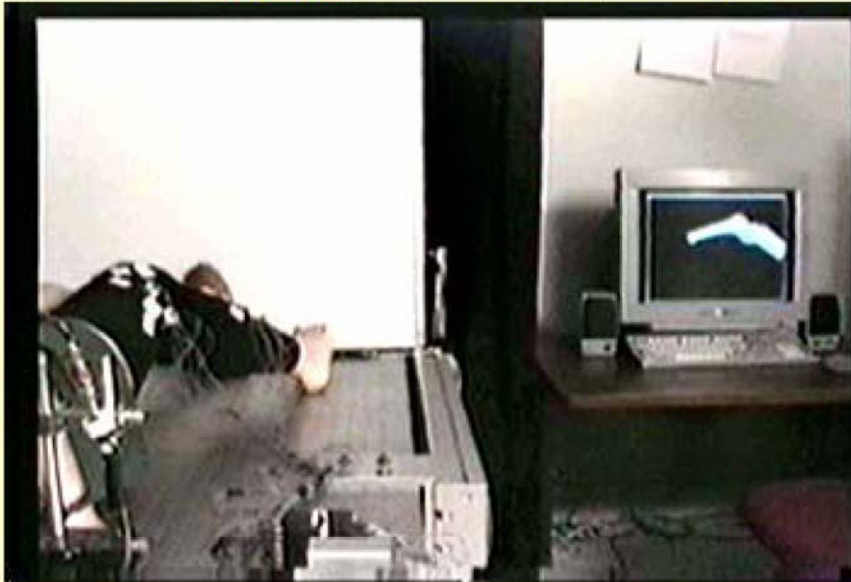


NIH - First Award 1997-2002

Methods Optics, Computer Vision, and Graphics



Development of a Kinematic Model of Joint Motion ([Baillot](#), Rolland et al., 2000)



Early Feasibility Experiments



First results in dynamic optical superimposition on an optical bench system

Featured in *Scientific American*, April 2002

Baillet et al., *Presence* 2000; Argotti et al., *Computers & Graphics* 2002



Visualization (Head-Worn Displays)

Cakmakci Ozan, and Jannick Rolland, Head-worn displays, *IEEE/OSA Journal of Display Technology*, 2(3) (September 2006).

C. Fidopiastis, L. Davis, J. Covelli, L. Nguyen, R. Martins, O. Cakmakci



Students: F. Hamza-Lup, A. Santhanam

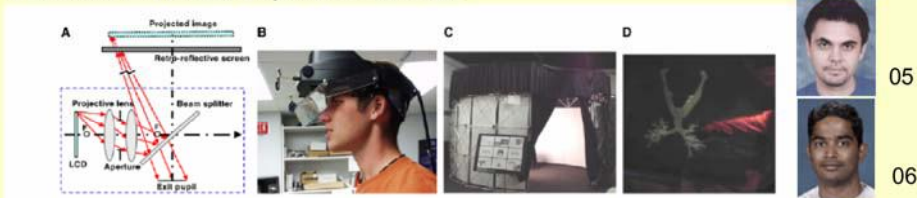




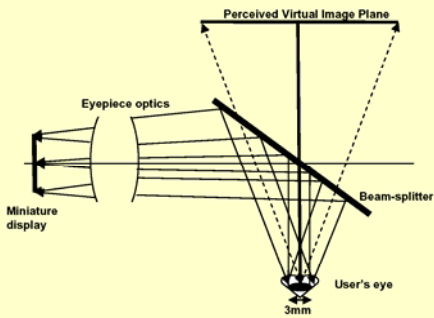
Fig. 5 HMPD in use in a deployable Augmented Reality Center (ARC): (A) Schematic of the HMPD optics; (B) user wearing a HMPD; (C) the ARC; and (D) user interacting with 3D models in the ARC. (View this art in color at www.dekker.com.)



Eyepiece versus Projection HMDs

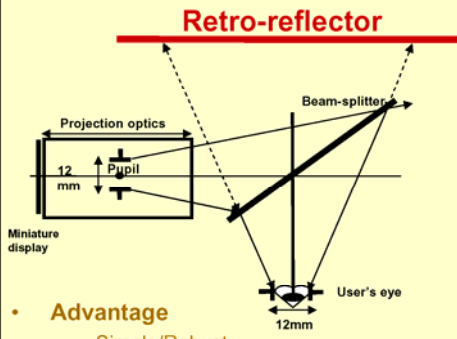


Eyepiece Optics (HWD)



- **Advantage**
 - Simple/Robust
 - Color
- **Challenge**
 - Optical weight scales with FOV
 - Distortion (electronic comp)
 - Illumination limited (miniature display)

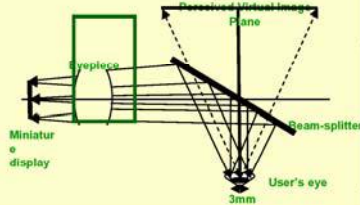
Head Mounted Projection Display



- **Advantage**
 - Simple/Robust
 - Color
 - Optics size does not scale with FOV
 - Lightweight
 - Distortion free
 - Lower aberrations than eyepiece design
- **Challenge**
 - Illumination limited by microdisplays
 - Screen type and location

Review of "Large FOV" Eyepiece Optics Design

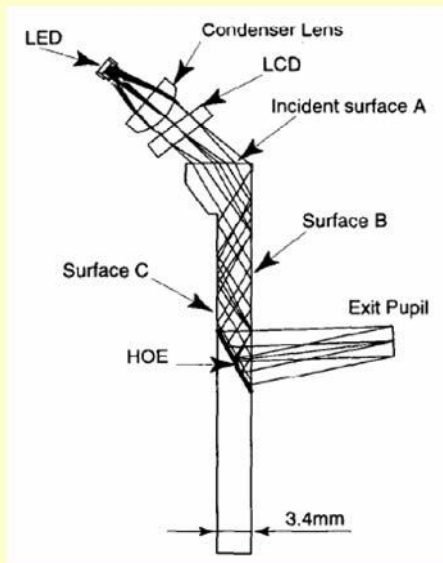
Rolland and Hua, 2005
Encyclopedia of Optical Engineering (Marcel Dekker)



Picture	Specification	Lens Form	Specification
	FOV 70 EFL 100 H. Erfle 1478704		FOV 70 EFL 100 Michael D. Missig 5446588
	FOV 33 EFL 34 J. D. Robinson C. M. Schor P. H. Muller W. A. Yankee eyepiece 5696521		 B. S. Fritz HMD using Manin Mirror combiner 5638490
	FOV 40-60 EFL 100 Takayoshi Toqino Eyepiece with DOE 6181475 5959780		FOV 40 15.2x12.3 MicroDisplay F#1.7 J.G. Drossler Honeywell, Inc Morristown, NJ 6147807
	FOV 50x60 J.G. Drossler D.J. Rotier Tilted Cat Ocular 1989		FOV 120 G. Anter Jean-Blaise Migozzi Holographic Binocular Helmet Visor 5124821
	FOV 50/60_color Helmet visor display B. Chen Off-axis Design 5526183		FOV 60_color 1.3" diagonal CRT J.P. Rolland Off-axis Design IODC94-OE-2000

Direct View
↓
See-through

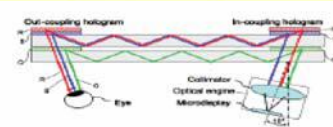
Related Work



Kasai. Int. Symp. Wearable Computers '00.



Resolution ~2 arcmins
FOV ~30 degrees
10 mm pupil [Lumus]



H. Mukawa et al. In Proc.
Society of Information
Display, 2008.

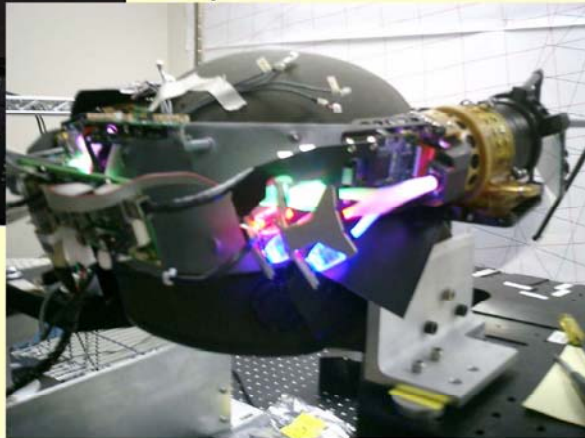
SONY

AHMD (Advanced HMD) Ultrawide FOV, off-axis design



Courtesy of LINK/ZYGO and
Optical Research Associates

Early 2000

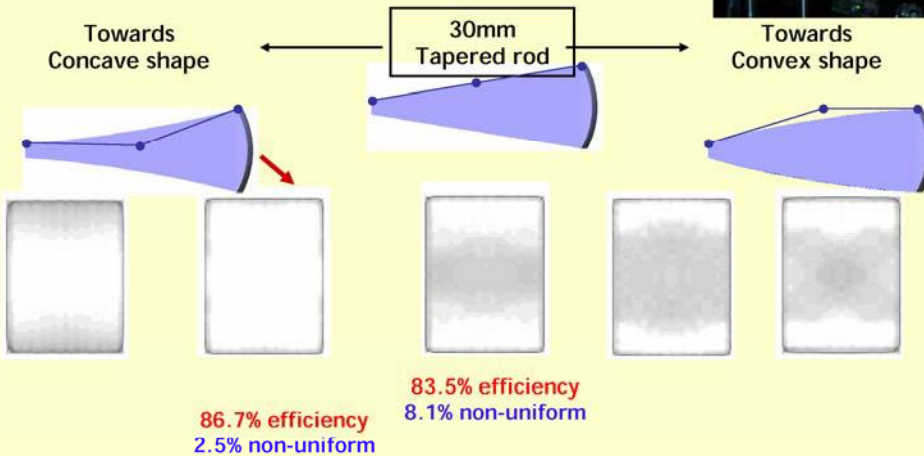
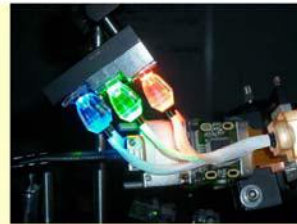


AHMD Specifications

Helmet compatibility	HGU-56P, HGU-55P all sizes
Center of gravity	Balanced
Eye relief	> 50 mm
Exit pupil	15 mm
Transmissivity	> 60%
Field-of-view	100° H x 50° V
Binocular overlap	30°
Resolution	1280 x 1024 per eye

Spatial Uniformity Behavior with Freeform Bezier Shapes

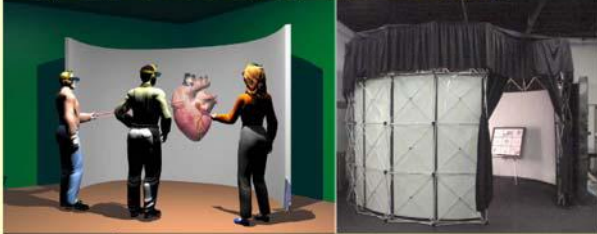
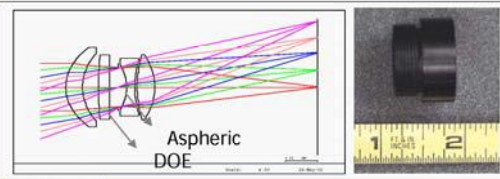
Fournier et al., Appl. Opt. 47 (2008) & OL 33(11) (2008)



Changing the concavity of the shape can improve uniformity
without sacrificing efficiency

Deployable Technology 1st Generation HMPD

with VGA LCD microdisplays
Hua, Ha, and Rolland, Appl. Opt. 42 2003



Fisher, 96 Patent

Miniaturization of
the Optics

Deployable Rooms



ODALab

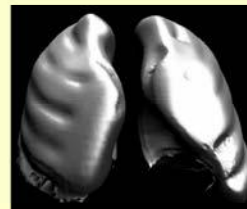
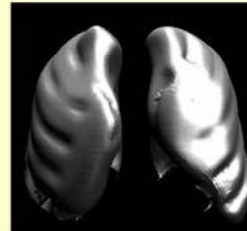
3D Visualization of the Upper Airway for Training Medics in Emergency Intubation Procedures

Augmented Reality Visualization

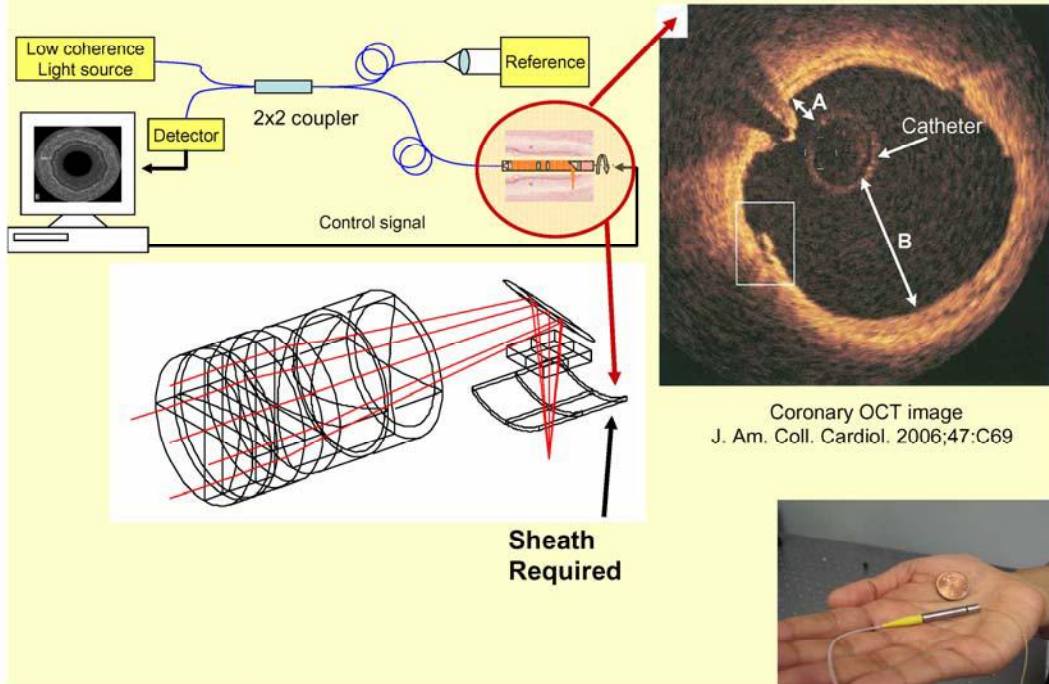


Lung Dynamics

Anand Santhanam, PhD 06



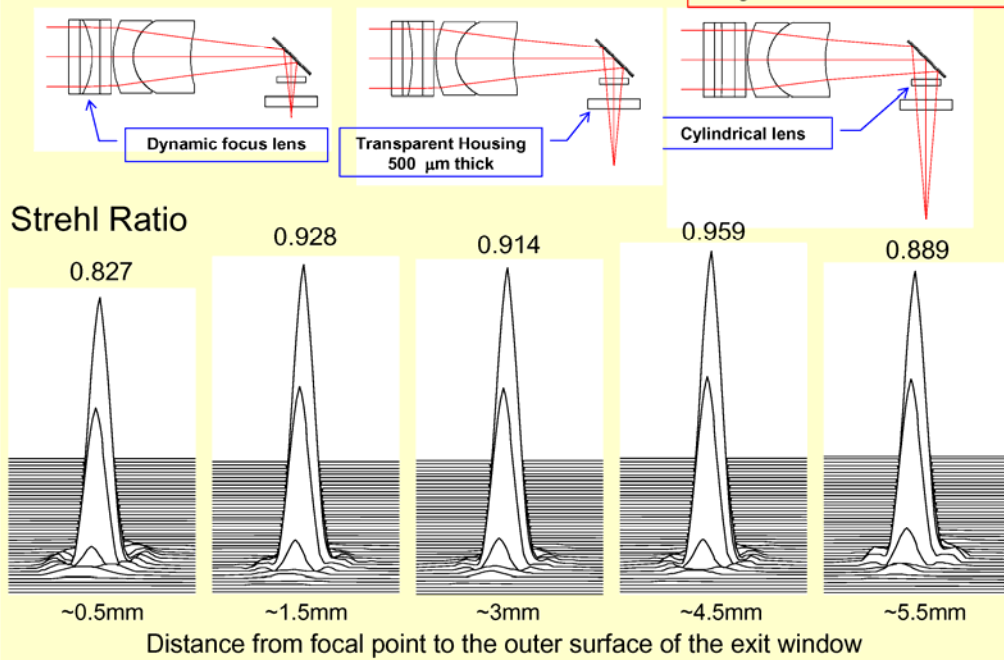
Imaging: Extended Depth of Focus Needed in Catheters



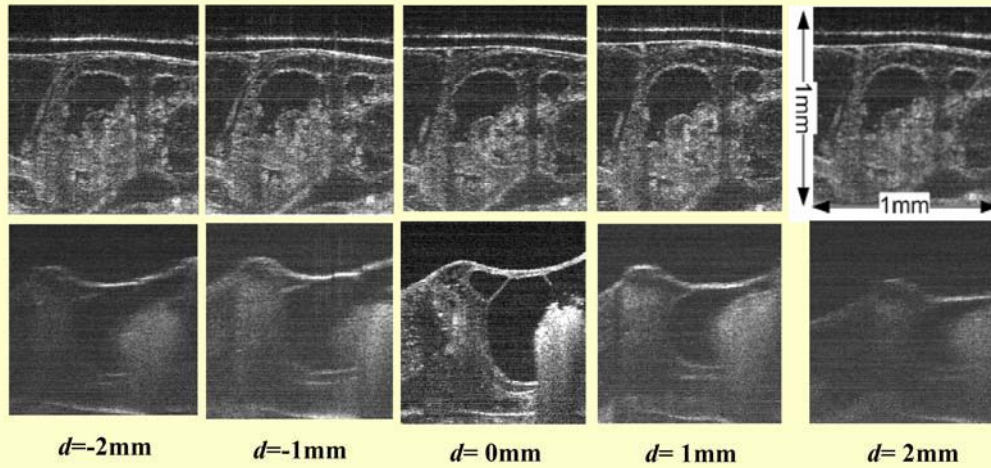
PSF through Working Range

Meemon et al., AO 2008

Target → Strehl ratio > 0.8



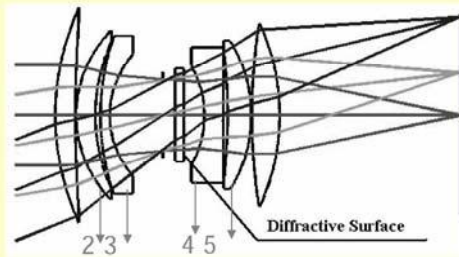
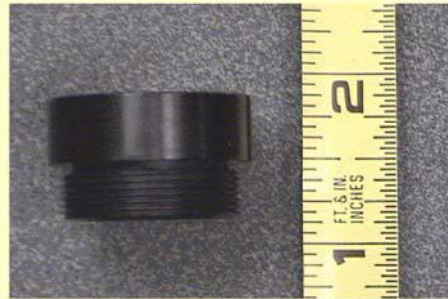
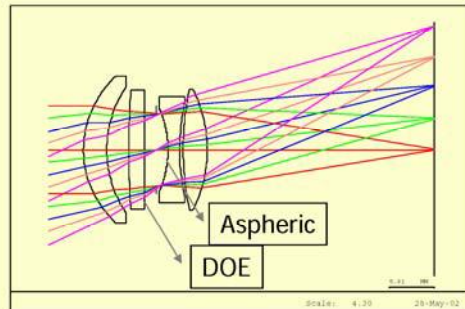
Bessel Beam vs. Conventional



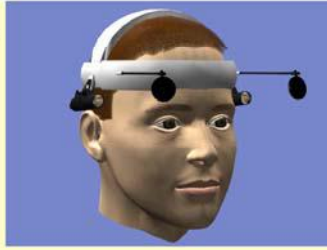
First Images of biological tissue acquired with a microlens axicon in a double pass OCT : Images of African frog (*Xenopus Laevis*) tadpole located at relative axial distances d from each medial position of its depth of focus.

K. Lee and J. Rolland *Optics Letters* 33 (2008)

52 deg. Lens / 8g per eye



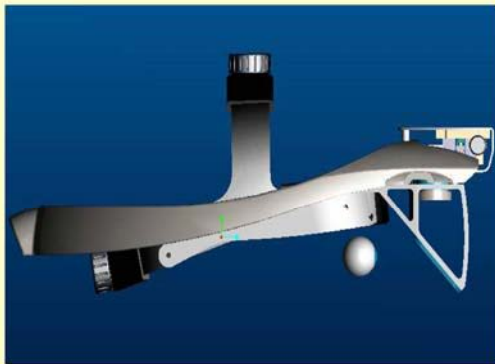
Teleportal Display UCF/MSU



Reddy et al., CVPR'04

42° FOV HMPD

Lightweight 595 grams - 2nd Generation HMPD using 800x600 OLED

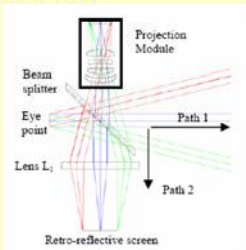


Optical Design done in the ODALab and
HMPD Optomechanical design done by Nvis Corporation
under SBIR program 2004-2005 with the US ARMY

M-HMPD - Fabric-free, Mobile

Martins, Optics Express 15(22), 2007

See-through, Outdoor
42° FOV



A recent experiment with the MD
Anderson Cancer Center Orlando
to appear in JDT, Dec08



Comparison of the ARC system with the 2D display system

To appear in Special Issue of JDT, Dec 08

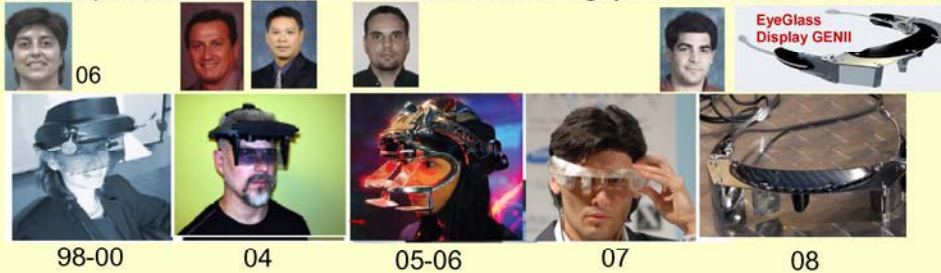
Subject	Average time (sec) Experiment 1		Average time (sec) Experiment 2		Average time (sec) Experiment 3	
	ARC	2D monitor	ARC	2D monitor	ARC	2D monitor
Expert 1	0	2.55	0.75	11.05	1.05	13.05
Expert 2	0	0.95	1.05	8.95	0.95	11.0
Expert 3	0.45	4.05	0.95	12.05	1.55	15.05
Expert 4	0	3.95	0.55	14.95	1.05	14.05
Expert 5	0.55	2.55	1.45	8.0	0.9	16.0
Expert 6	0	3.45	1.40	9.0	1.55	13.0
Average	0.2	2.9	1.0	10.7	1.2	13.7

The individual dose beams are delivered to a patient in 30-40 seconds, Thus, a 10 second delay in decision making is highly significant

Visualization (Head-Worn Displays)

Cakmakci Ozan, and Jannick Rolland, Head-worn displays, IEEE/OSA *Journal of Display Technology*, 2(3) (September 2006).

C. Fidopiastis, L. Davis, J. Covelli, L. Nguyen, R. Martins, O. Cakmakci



Students: F. Hamza-Lup, A. Santhanam

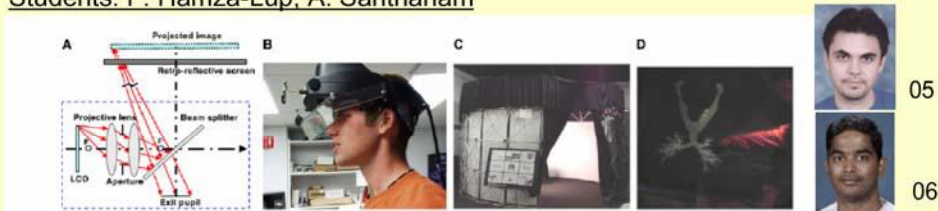


Fig. 5 HMPD in use in a deployable Augmented Reality Center (ARC): (A) Schematic of the HMPD optics; (B) user wearing a HMPD; (C) the ARC; and (D) user interacting with 3D models in the ARC. (View this art in color at www.dekker.com.)

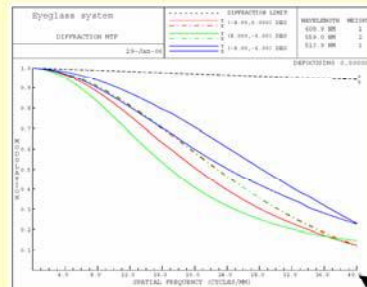
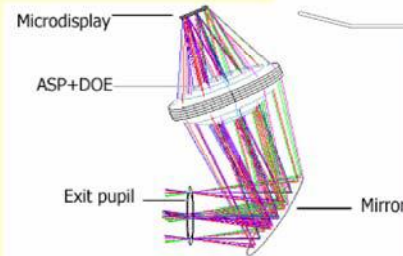
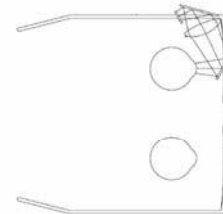
FREE FORM OPTICS



Eyeglass Display

Ozan Cakmakci, *Kidger Scholarship 05*

Cakmakci & Rolland, *Journal of Display Technology*, (2006).



40 cycles/mm

Dual-element Solution



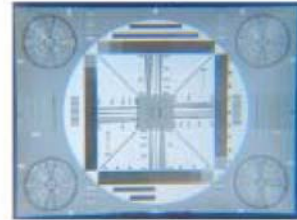
Cakmakci & Rolland, OL 32(11), 2007



Field of view: up to 25 FOV diagonal
Resolution: ~1.5 arcminutes
Exit pupil size: up to 12mm
Eye clearance: >15 mm
Distortion: <4%
Wavelengths: 450-650nm



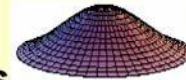
(a)



(b)

Fig. 2. (Color online) Photograph through the fabricated dual-element system of (a) a color target and (b) a black and white target.

We Propose to Design Freeform Optical Surfaces whose Representations use **Local Basis Functions** (as Opposed to Global Polynomials)

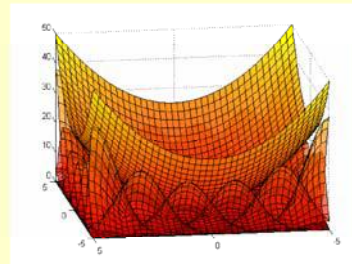


- An optical surface can be represented as a sum of basis functions

$$z(x, y) = \sum \phi_i(x, y)w_i$$

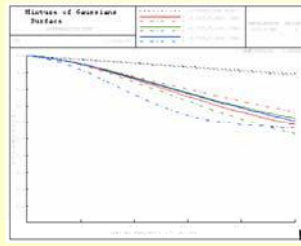
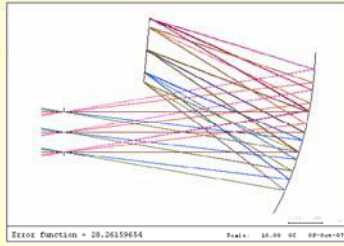
- In matrix form

$$z = \Phi W$$



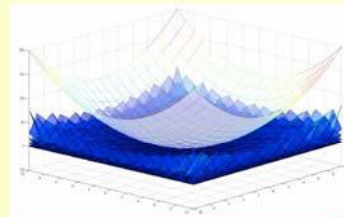
- To be invertible, Φ must be positive definite. equivalent to having positive eigenvalues.

Results



Surface type	Average MTF	Max. Distortion
Anamorphic asphere	26.5%	3.8%
X-Y polynomial	43.6%	2.65%
Zernike polynomial	42%	3.74%
Lin. Comb. of Gaussians	60.5%	3.6%

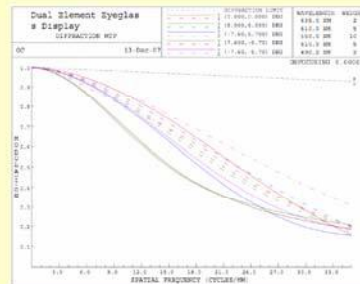
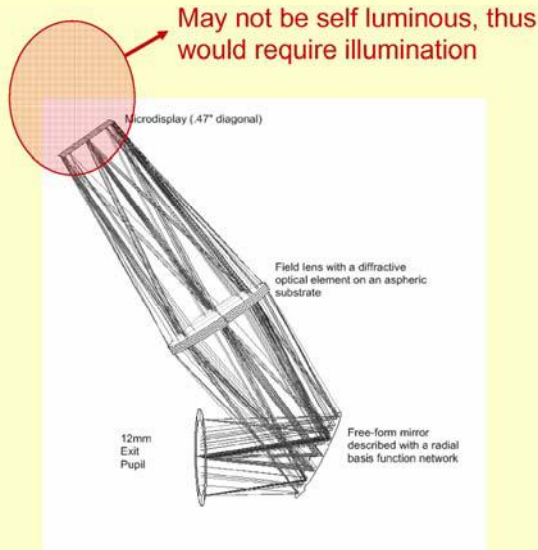
40 cycles/mm



Cakmakci et al., Optics Express 16(3) (2008)

Revisiting the Dual-Element Design: Pupil Size Expansion

Cakmakci et al. OL (April 2008)



Using a 16x16 set of basis functions.



Won 1st place
in the 2007 CTIA
Wireless
Technology
Student
Competition

EyeGlass Display
GENII



The EyeGlass Display



Acknowledgements

- National Institute of Health (NIH/NLM) First Award (5years)
- National Science Foundation
 - EIA 99-86051, IIS/ITR00-82016, IIS/HCI 03-07189
- Office of Naval Research
 - N00014-02-1-0261, N00014-02-1-0927, N00014-03-1-0677 ...
- US Army STRICOM, US Army Medical Res., US AirForce
- NASA
- Florida Photonics Center of Excellence
- Industry Partners: METI Corporation, NVIS Corporation, Optical Research Associates

