OPTICAL INTERFERENCE COATINGS

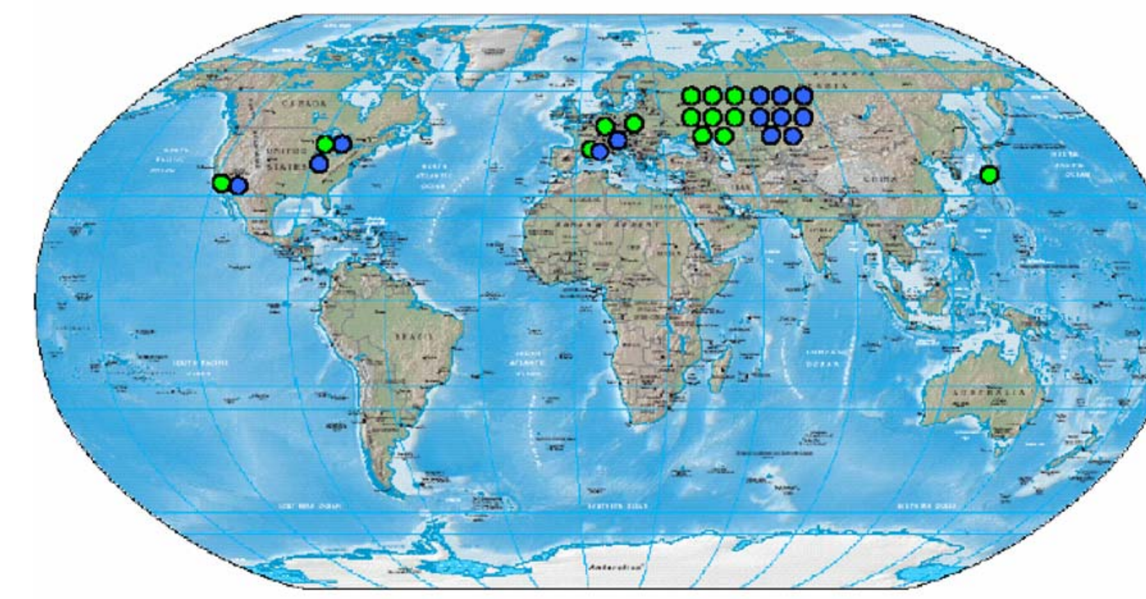
Tucson 2004

DESIGN CONTEST

Organized by *Pierre Verly* CNRC·NRC

and *Markus Tilsch* JDS Uniphase

Submissions



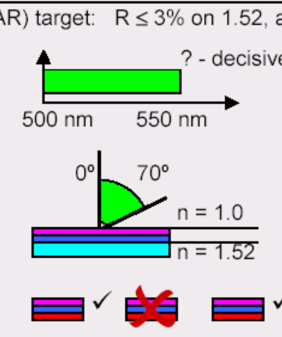
- 13 submissions for problem A
- 12 submissions for problem B

More information:
http://www.osa.org

DESIGN PROBLEM A

Problem A Introduction

Antireflection coating (AR) target: R ≤ 3% on 1.52, average polarization



- Broadband
- Broad-angle — tested at 0°, 20°, 40°, 55°, 60°, 65°, and 70°
- Manufacturable — ≥ 50% yield for 1nm rms error

Materials: 1.38, 1.45, 1.65, 1.8, 2.05, 2.35, non-dispersive, non-absorptive

Maximum number of layers: 35 Minimum physical layer thickness: 5 nm

References:

J. A. Dobrowolski et. al., "Toward perfect AR coatings", Appl. Opt. **41**, 3075-3083 (2002)

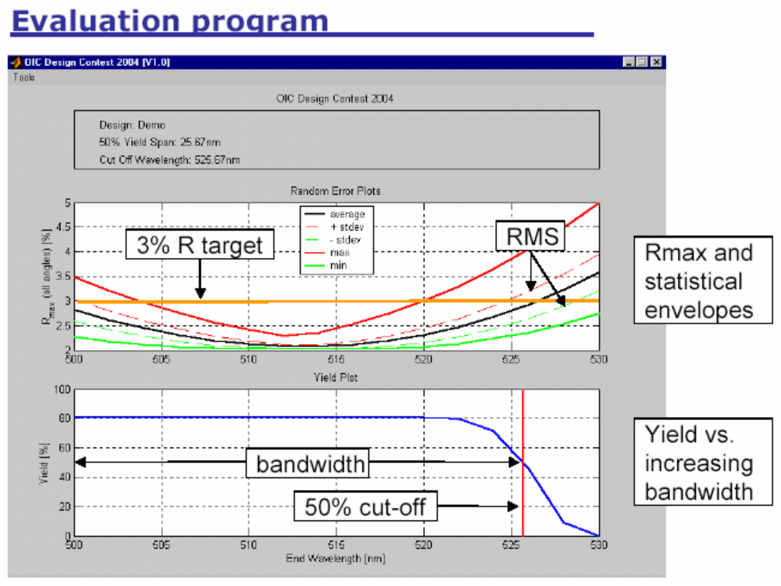
J. A. Dobrowolski, "Optical properties of films and coatings," in Handbook of Optics, M. Bass, ed. (McGraw-Hill, NY, 1995), p. 42.19 – 42.34

G. DeBell, Proc SPIE 401, 127-137 (1983)

Problem A design specifications: broadband, wide-angle AR coating

- *Maximize* AR bandwidth (500 - ??? nm)
- Angles = *0*, 20, 40, 50, 55, 60, 65, *70 degs*.
- *R<3%*, average polarization
- *Glass* substrate (n=1.52)
- *n = 1.38*, 1.45, 1.65, 1.80, 2.05, 2.35
- *50% yield*, 1nm random optical thickness errors (RMS)
- *≤ 35 layers*
- Layer *t* ≥ 5nm

Evaluation program



Contest results

#	Design	Width (nm)	Author	Address
1	DebeTru1	68.01	G. Debell, M. Trubetskov	Debell Design and MSU
2	Amotchk1	66.22	Tatiana Amotchkina	MSU (Moscow State U.) - Russia
3	Amotchk2	66.15	Tatiana Amotchkina	MSU
4	Lemarchand	66.09	Fabien Lemarchand	Institut Fresnel - France
5	Trubets1	64.60	Michael Trubetskov	MSU
6	SharapA1	61.22	Dmitri Sharapov	MSU
7	YagolaA1	61.03	Svetlana Yagola	MSU
8	YagolaA2	60.43	Svetlana Yagola	MSU
9	SharapA2	60.25	Dmitri Sharapov	MSU
10	Southw2	59.11	Bill Southwell	Table Mountain Optics - USA
11	Schultz	58.14	Ulrike Schulz, Minghong Yang	Fraunhofer IOF - Germany
12	Fan2	55.07	Bin Fan	Optorun Co - Japan
13	Oliver1	48.41	James Oliver	U. of Rochester - USA
14	Demo	25.67	OIC2004 demo solution	
	Verly *	66.10	Pierre Verly	NRC - Canada

* Non contest

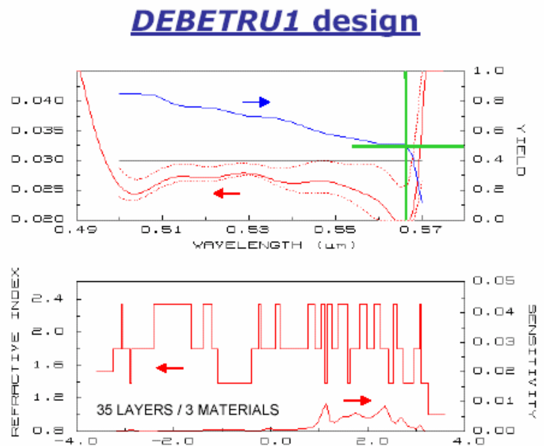
Stability of the top designs (5,000 random-error iterations)

- Fluctuations > differences between the results
- Lemarchand is very stable
- Same set of random numbers used for all the designs in a given test

Tests with 50,000 iterations ++

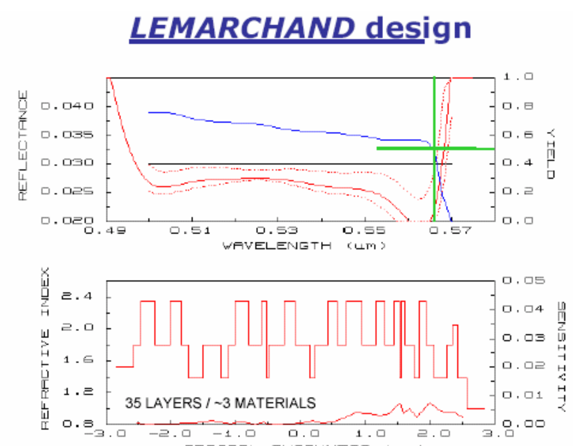
#	Design	Widths (nm): 2 x 50,000 iters (NRC)	Widths (nm): 100 x 5,000 (TOL_OIC04)	Widths (nm): Average	Widths (nm): Contest	Contest #
1	DebeTru1	66.34	66.33	66.34	68.01	1
2	Lemarchand	66.11	66.13	66.12	66.09	4
3	Amotchk2	66.01	65.94	65.97	66.15	3
4	Amotchk1	65.05	65.01	65.03	66.22	2
5	Trubets1	64.23	64.26	64.25	64.60	5
6	YagolaA1	61.68	61.69	61.68	61.03	7
7	SharapA1	61.45	61.41	61.43	61.22	6
8	YagolaA2	60.65	60.63	60.64	60.43	8
9	SharapA2	60.45	60.47	60.46	60.25	9
10	Southw2	58.59	58.55	58.57	59.11	10
11	Schultz	58.04	58.01	58.03	58.14	11
12	Fan2	55.06	55.05	55.06	55.07	12
13	Oliver1	48.60	48.64	48.62	48.41	13
14	Demo				25.67	14
	Verly	66.11		66.11	66.10	

DEBETRU1 design



- Thick, 3-material solution (possibility of 6 materials)
- The yield curve is flat near 50% => AR width instability

LEMARCHAND design



- Thick, (almost) 3-material solution
- Yield curve is higher above 50% => better AR width stability
- Very smooth reflectance & yield curves

Design control

- Starting designs: multiple random, rugate, wideband AR, none, etc.
- Thick layers on the substrate side
- Desensitization: suppression or modification of sensitive thin layers (index or thickness changes)
- Target definition & progressive tuning:
  - AR widths, tolerances, reflectance values, qualifiers (=, <, >), etc.
  - Control of the perturbed reflectance curves (RMS envelopes).

Design techniques

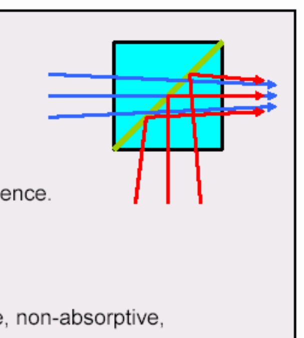
Author	Software	Approach
Debell / Trubetskov	OptiLayer + plug in	Needle synthesis + optimization of non-smooth functions
Lemarchand	Own software *	Needle + global optimization + directed TF synthesis
Amotchkina	OptiLayer	Directed TF synthesis
Yagola	OptiLayer	Refinement + directed TF synthesis
Sharapov	OptiLayer	Refinement + directed TF synthesis
Southwell	OptiLayer + LayerPro	Needle + target optimization
Schultz	OptiLayer	Needle + directed TF synthesis
Fan	Essential Macleod	Directed TF synthesis
Oliver	OptiLayer	Directed TF synthesis
Verly	NRC	Inhomogeneous refinement + Needle

DESIGN PROBLEM B

Problem B Introduction

'Minimum shift' immersed short pass filter

- R_p > 98% from 575 to 675 nm
- T_p > 94% from 425 to 525 nm



Winning design has highest angular tolerance in a cone of light centered around 45° angle of incidence.

Materials:

1.38, 1.45, 1.65, 1.8, 2.05, 2.35, non-dispersive, non-absorptive, **non-dispersive silver (0.055 + 3.32i)**

Substrate index: 1.52

Maximum number of layers: 100 Minimum physical layer thickness: 5 nm

References:

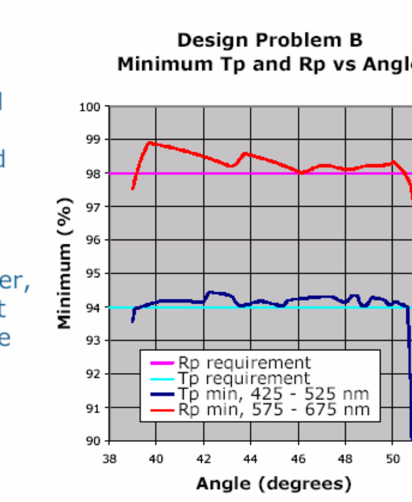
A. Thelen, "Design of Optical Interference Coatings", (McGraw-Hill, NY, 1989), Chapter 9

H. A. Macleod, "Thin Film Optical Filters", (Institute of Physics Publishing, London,2001), Chapters 6 and 8

P. Baumeister, "Optical Coating Technology", UCLA Short Course Notes, Chapter 5

Evaluation procedure

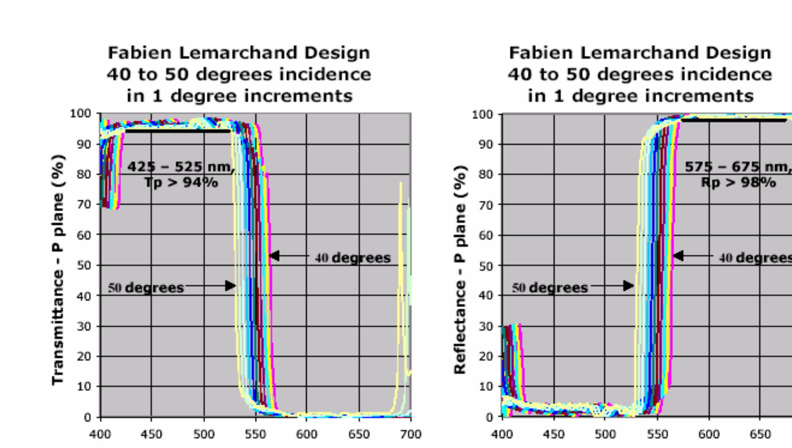
- Performance evaluated from 400 to 700 nm in 0.1 nm increments and from 39 degrees to 51 degrees in 0.1 degree increments
- To determine the winner, a finer angle increment was used: 0.01 degree increments



Contest results

	Submitted by	Valid Angle Range (degrees from 45°)
1	Fabien Lemarchand *	± 5.52
2	Michael Trubetskov 1	± 5.51
3	Tatiana Amotchkina 2	± 5.23
4	Bill Southwell	± 5.20
5	Michael Trubetskov 2	± 5.16
6	Dave Cushing	± 5.12
7	Tatiana Amotchkina 1	± 4.98
8	Svetlana Yagola 1	± 4.71
9	Dmitri Sharapov 1	± 4.67
10	Dmitri Sharapov 2	± 4.60
11	Svetlana Yagola 2	± 4.58
12	James Oliver	± 2.00

Sample performance plots



Trends in design submissions

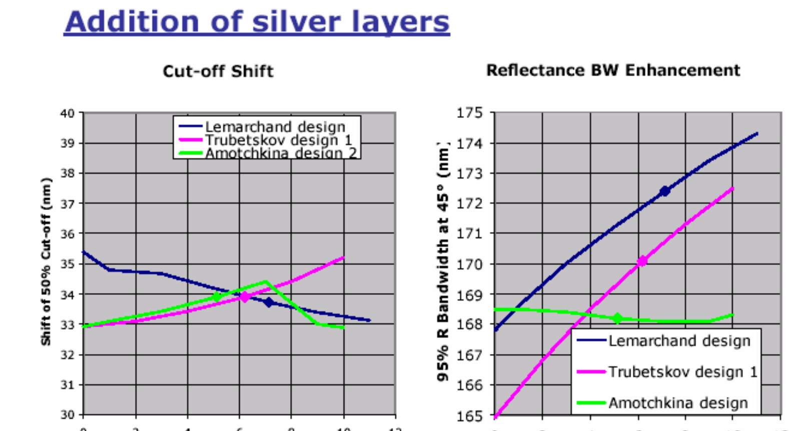
Submitted by	Layers	Thinnest layer	Total thickness	Indices used
(Units)	(#)	(nm)	(μm)	
Requirement	≤ 100	≥ 5	≤ 50.0	1.38, 1.45, 1.65, 1.8, 2.05, 2.35, Ag
Fabien Lemarchand	100	7.2	9.9	1.65, 2.35, Ag
Michael Trubetskov 1	100	6.2	10.9	1.65, 2.35, Ag
Tatiana Amotchkina 2	100	5.1	10.8	1.65, 2.35, Ag
Bill Southwell	100	12.3	10.1	1.38, 1.65, 2.35
Dave Cushing	99	57.6	10.0	1.45, 1.65, 1.8, 2.35
Michael Trubetskov 2	99	70.4	10.5	1.65, 2.35
Tatiana Amotchkina 1	99	72.8	10.8	1.65, 2.35
Svetlana Yagola 1	99	45.8	10.0	1.45, 1.65, 1.8, 2.05, 2.35
Dmitri Sharapov 1	99	45.8	10.0	1.45, 1.65, 2.05, 2.35
Svetlana Yagola 2	99	45.3	9.9	1.45, 1.65, 1.8, 2.05, 2.35
Dmitri Sharapov 2	99	45.8	10.0	1.45, 1.65, 1.8, 2.05, 2.35
James Oliver	87	5.0	10.1	1.45, 1.65, 1.8, 2.35, Ag

- Generally, the maximum number of layers were used (100)
- Indices chosen always include 1.65, 2.35
- Top 3 winning designs use one thin layer of silver (Ag)

Design approaches for submissions

- Starting mirror design using 1.65/2.35 selected by almost all designers.
- Optimization methods included damp least squares, gradual evolution, Newton method, conjugate gradients method and direct synthesis.
- Other materials and layers added using needle optimization and gradual evolution.
- Some designs were started using an analytical design, while others were computer generated.
- Silver added to suppress reflectance dips, but only thin layers could be used without effecting transmission band.

Addition of silver layers



- Addition of silver layer can broaden reflectance band
- Addition of silver layer has a mixed influence on angle shift
- Widening of the reflectance band is the dominant effect

Problem B Conclusions

- The limit on the number of layers (100) dictates the indices chosen. There is a tradeoff between:
  - Stopband width
  - Reflectance level
  - Angle shift
- The addition of one thin silver layer improves the design performance by widening the reflectance region.

Thank you to all of the Contributing Designers!

* *F. Lemarchand Global Optimization Design Technique*

- Home made-program using a global optimization procedure developed by T. Csendes et Al. in respiratory system modelling.
- The multi-dimensional space composed of the different parameters (thickness) is divided into clusters formed by single linkage method.
-The distance between a set of initial parameters X_0 and the parameters X_{10} corresponding to the local minimum found is evaluated. A new point X_1 will join the (X_0; X_{10}) cluster if there is a point in the cluster with which the distance is less than a critical distance calculated automatically by the program. If the new point is not clustered, a new local minimum X_{11} is searched.
- The process is repeated until the whole space, possibly reduced to a nominal interval is clustered. The local search procedure is an algorithm of Quasi-Newton type which uses the Davidon-Fletcher-Powell formula.

For more details, see

T. Csendes, B. Daroczy, Z. Hanos, *"Nonlinear parameter estimation by global optimization: comparison of local search methods in respiratory system modelling"*, System Modelling and Optimization, 188-192, Springer Verlag, Berlin, 1986