Линзы Френеля для концентрирования солнечного излучения

(Fresnel lenses for sunlight concentration)

Лаборатория фотоэлектрических преобразователей

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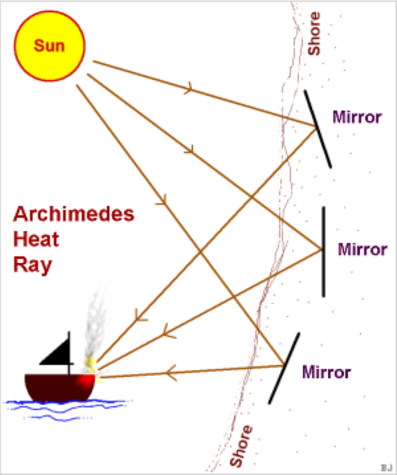
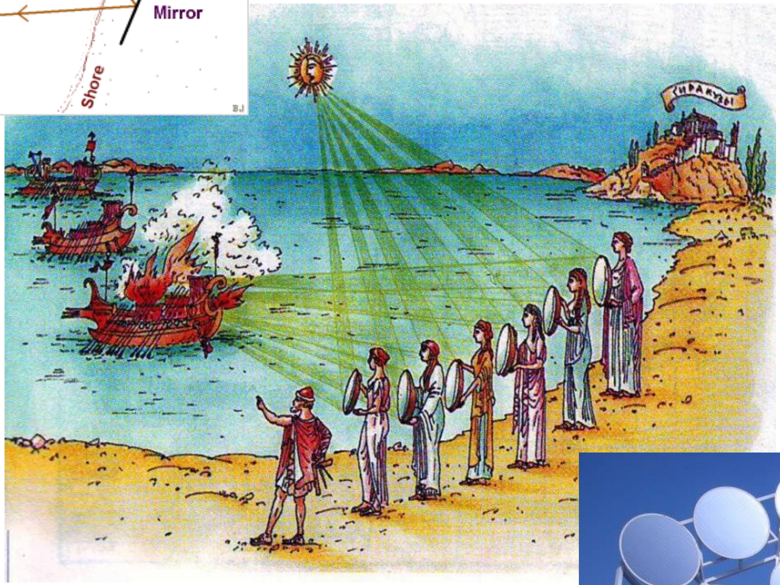
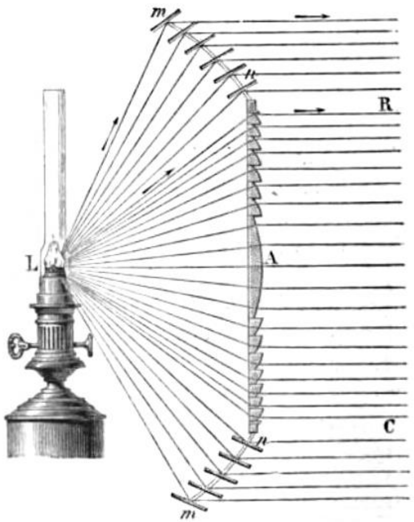
History of sunlight concentration: mirrors

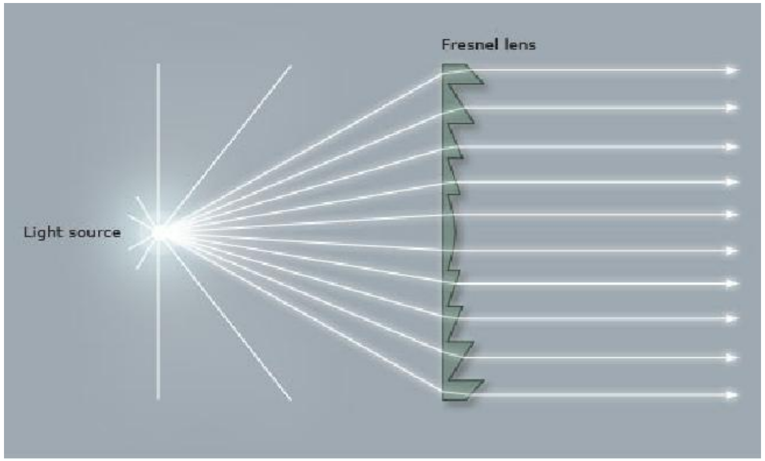




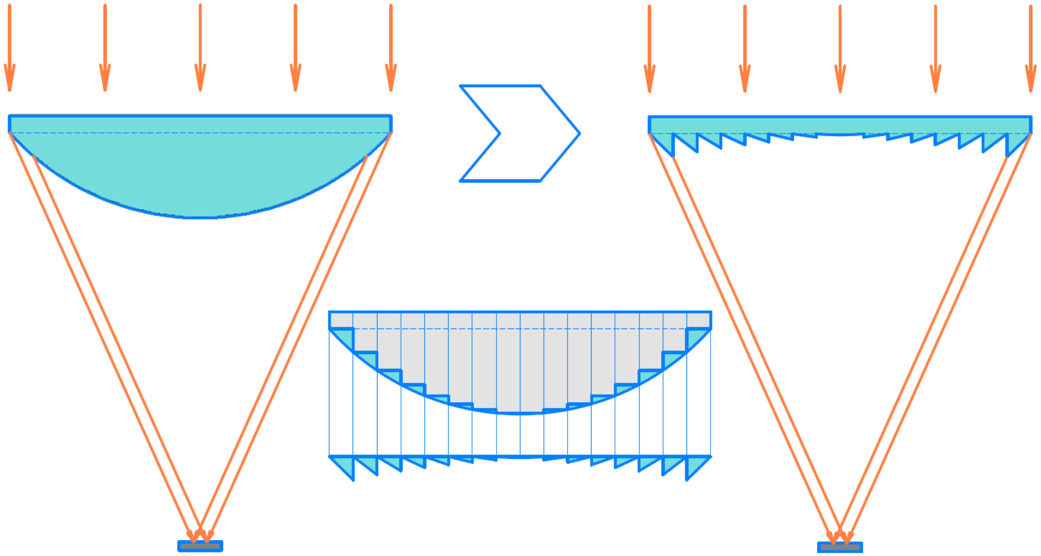
214-212 B.C.

History of sunlight concentration: lenses



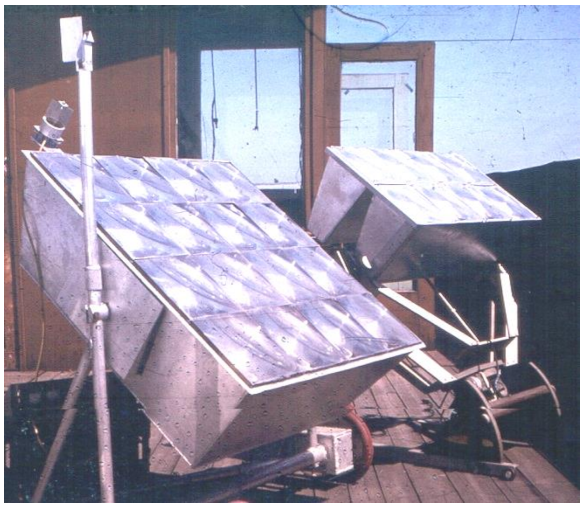


Augustin-Jean Fresnel
~1823 year



History of concentrator PV activity at the Ioffe Institute

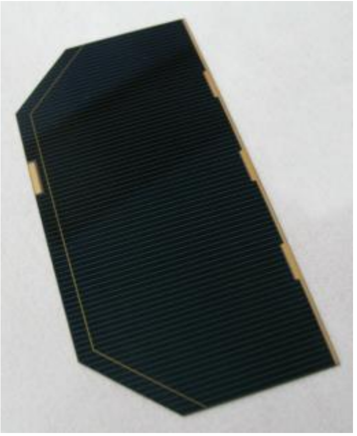
PV installation with large GaAs SC and parabolic mirrors and heat pipes (early 1980s)

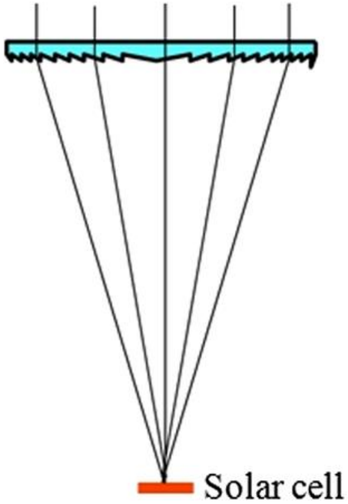


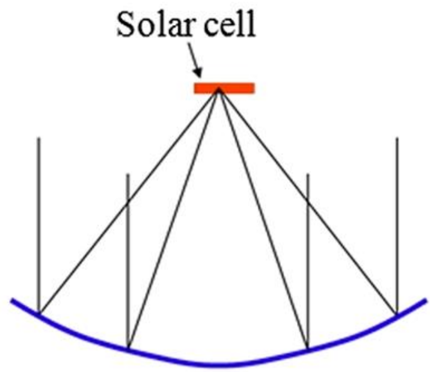
Concentrator modules with GaAs SC, acrylic Fresnel lenses and Al heat sink (middle 1980s)

Concentrator modules with smooth lenses, and small AlGaAs/GaAs SC (last 1980s)

The tendency in concentrator PV:
from large to small concentrators at high concentration ratio!

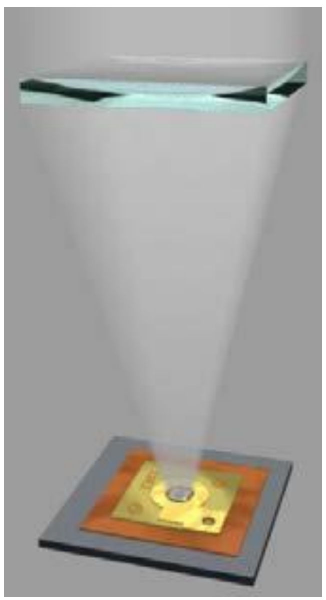


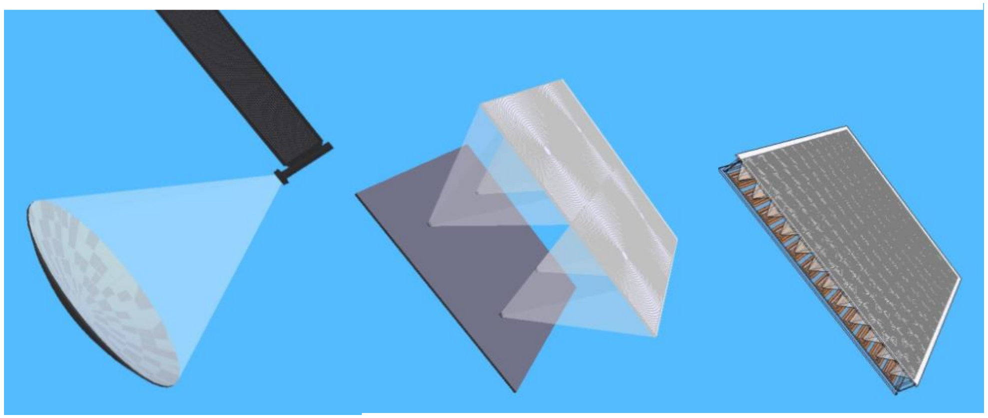




<u>The key trend in concentrator photovoltaics:</u>

from large to small concentrators and solar cells while maintaining a high concentration ratio of solar radiation (500 ÷ 1000 times or more)

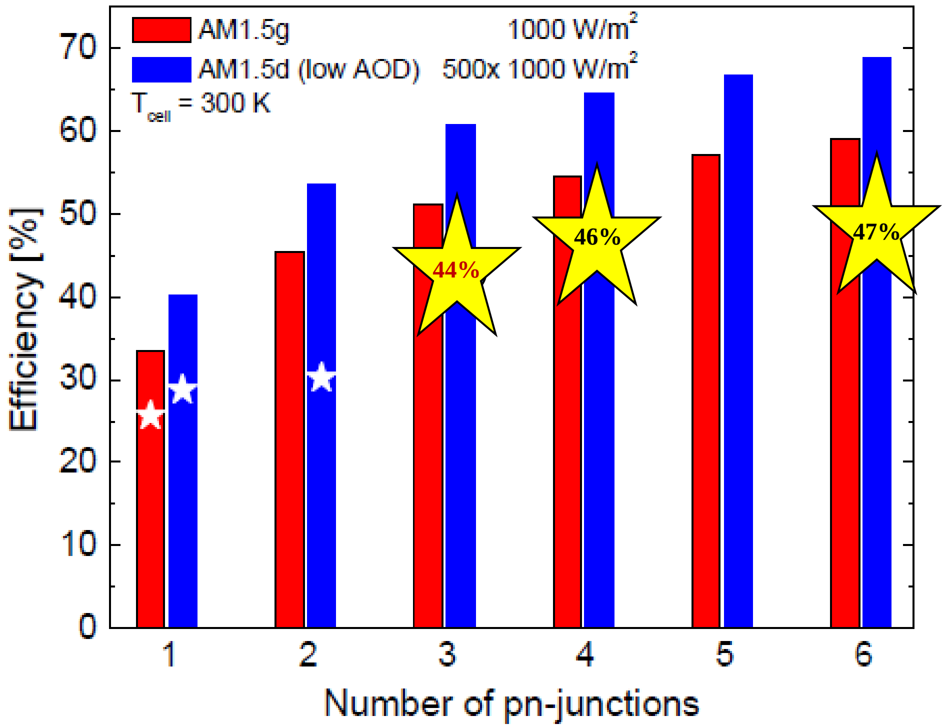




Benefits of MJ concentrator SCs and practical achievements

⇒ η increases with the number of pn-junctions

⇒ η for concentrator cell is higher



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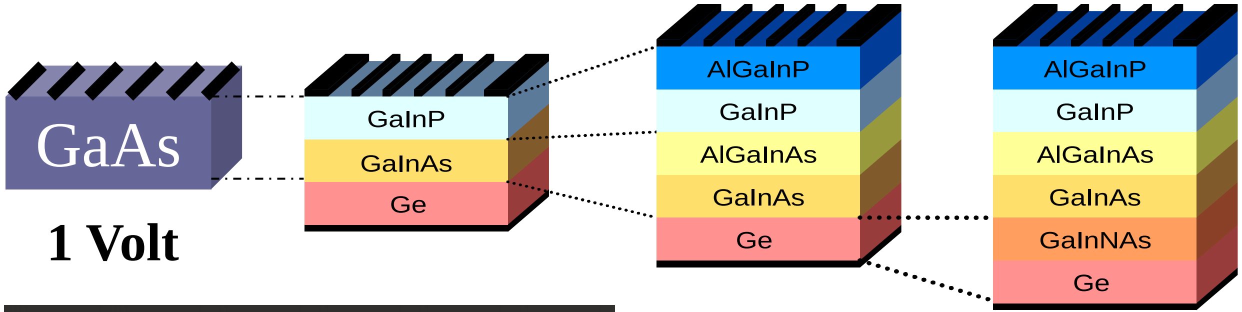
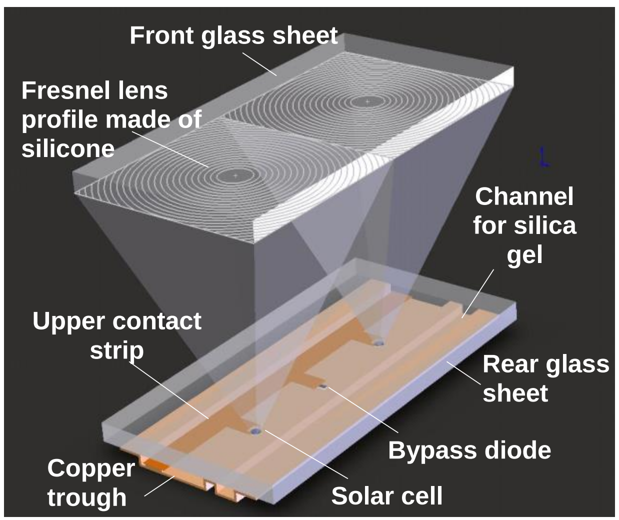
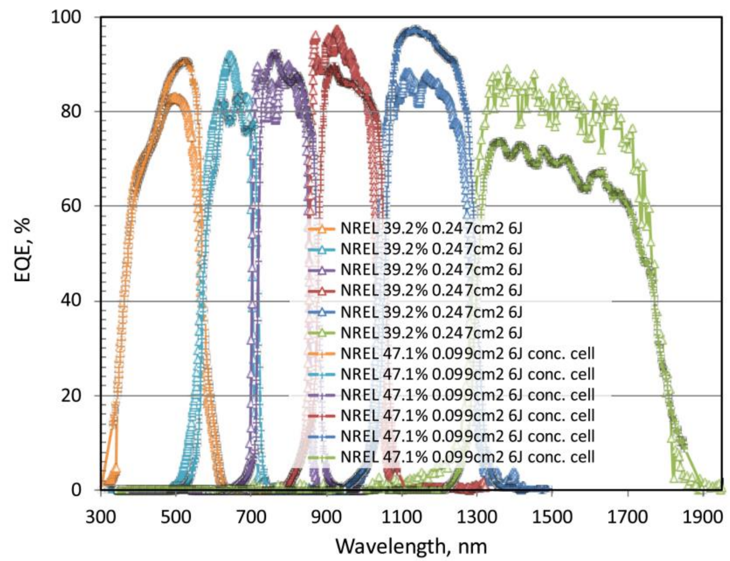
III-V concentrator solar cells : from one to three- and more-junction cells- to higher voltages and reduced photocurrent densities!





A section of a module structure ("all-glass" design) based on 2 Fresnel lenses and 2 multijunction solar cells



47% - 6-junction SC with inverted metamorphic structure (NREL, USA)

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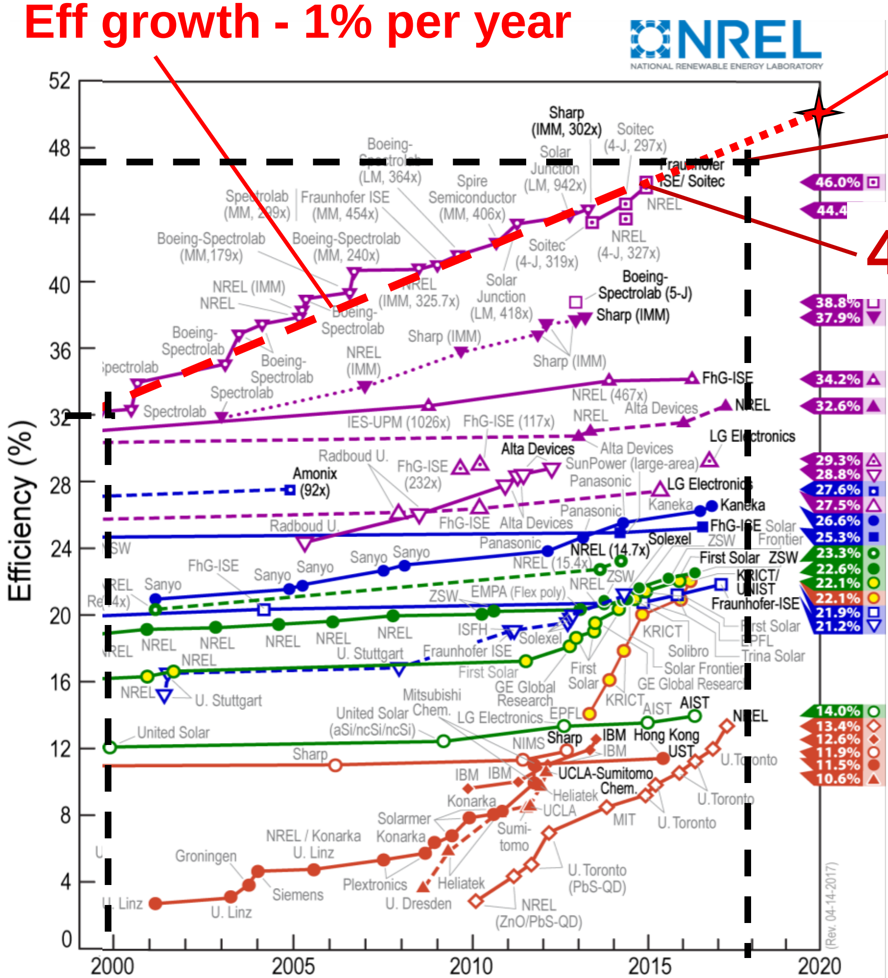
Conversion efficiency trends of terrestrial solar cells of various types and concentrator modules

Eff growth - 1% per year

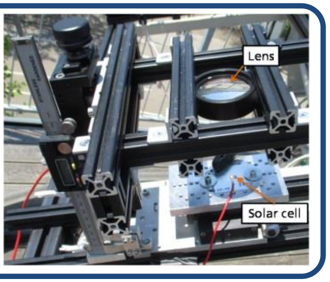
50%

6J- 47.1%

4J- 46%



43.4% Submodule (1 unit, 340X)



41.4 % Module (10 units, 333X)

This plot is courtesy of the National Renewable Energy Laboratory, Golden, CO

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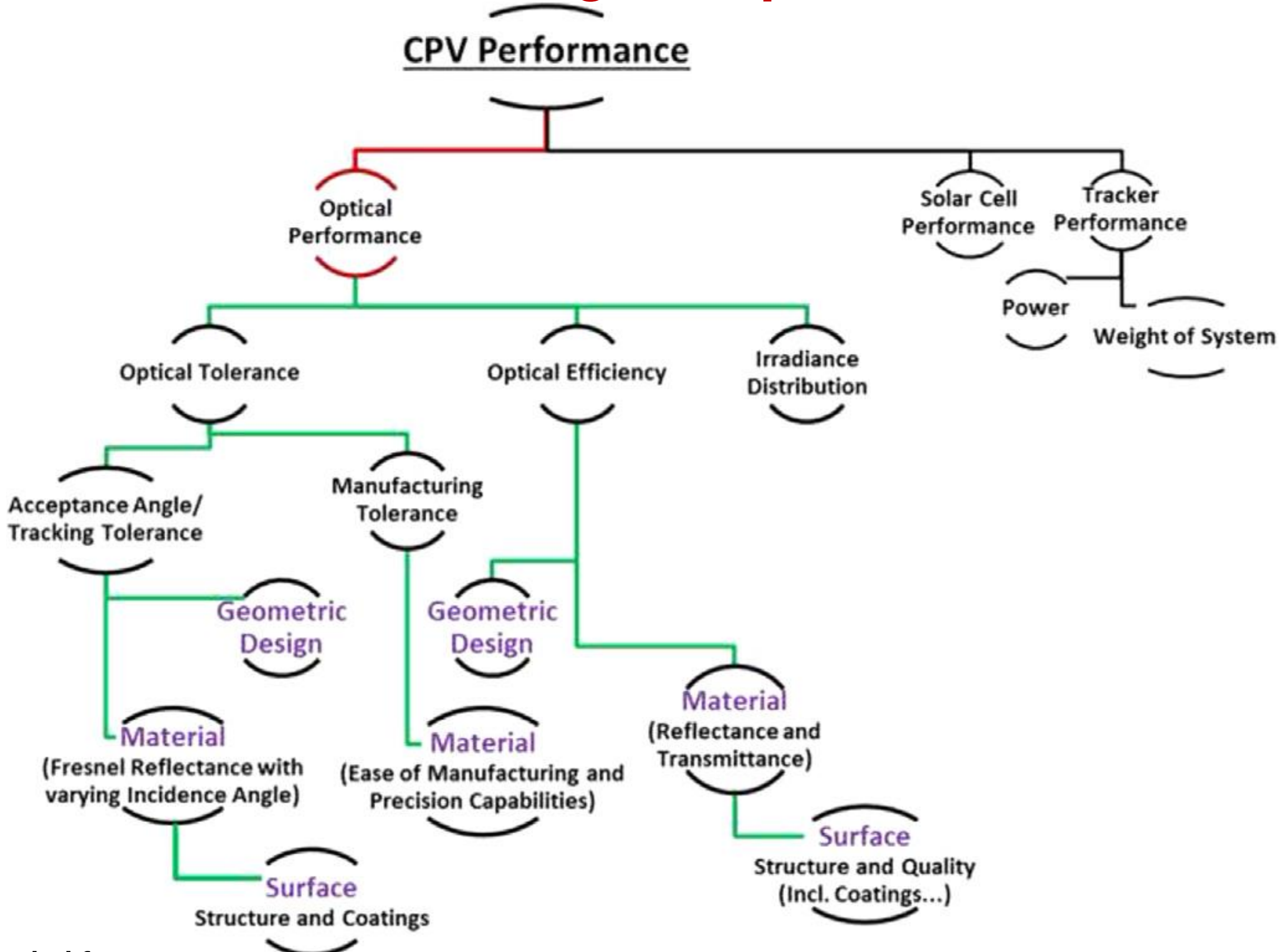
Factors affecting CPV performance.



This plot is copied from:
Katie Shanks, S. Senthilarasu, Tapas K. Mallick, "Optics for concentrating photovoltaics: Trends, limits and opportunities for materials and design", Renewable and Sustainable Energy Reviews 60 (2016) 394–407.

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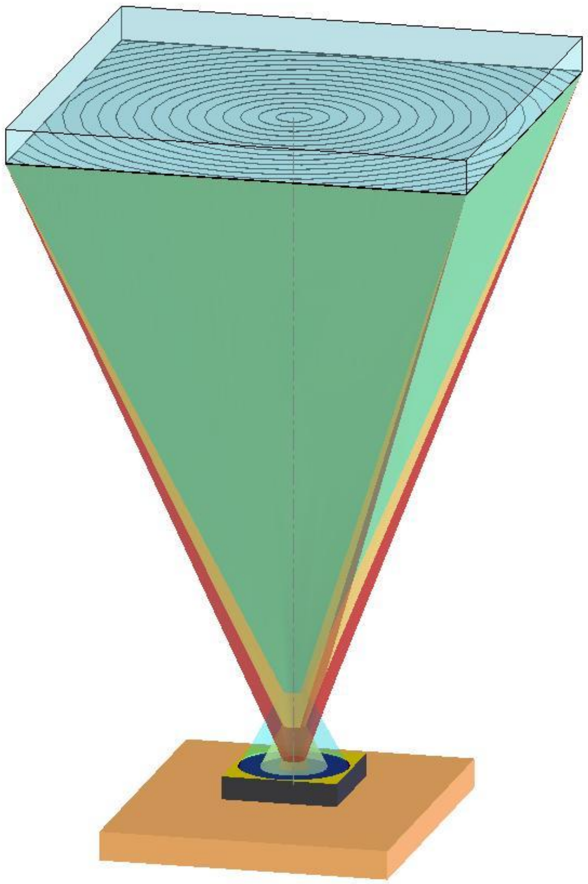
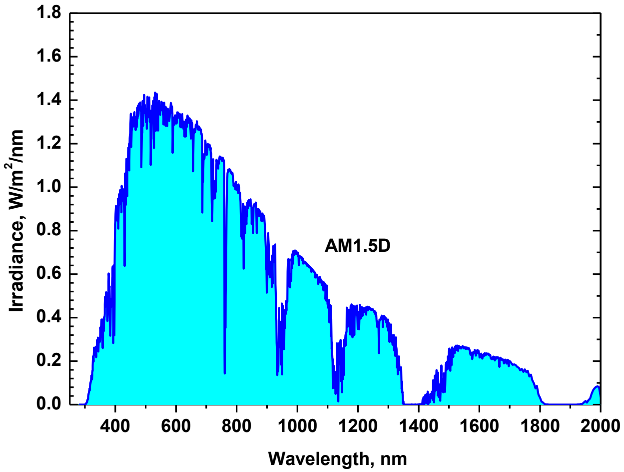
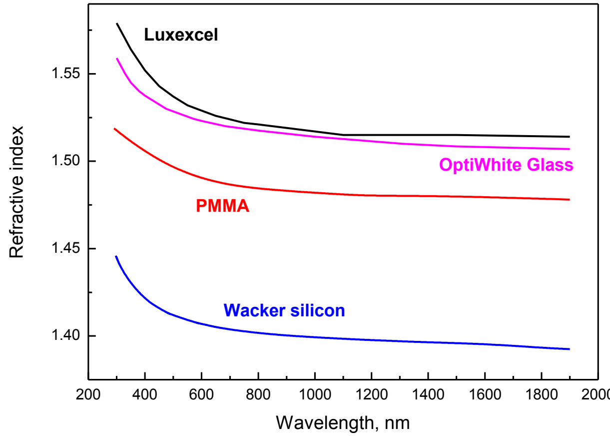
OUTLINE



- ❖ Approaches and criteria of FL optimization
- ❖ Materials for FL
- ❖ Fresnel lens manufacturing
- ❖ Geometrical imperfections of FL
- ❖ Correlations between construction and optical parameters
- ❖ «FLCon» software
- ❖ Optimal FLs for different applcations
- ❖ Conclusions

Ray-tracing and chromatic aberration in refractive optics





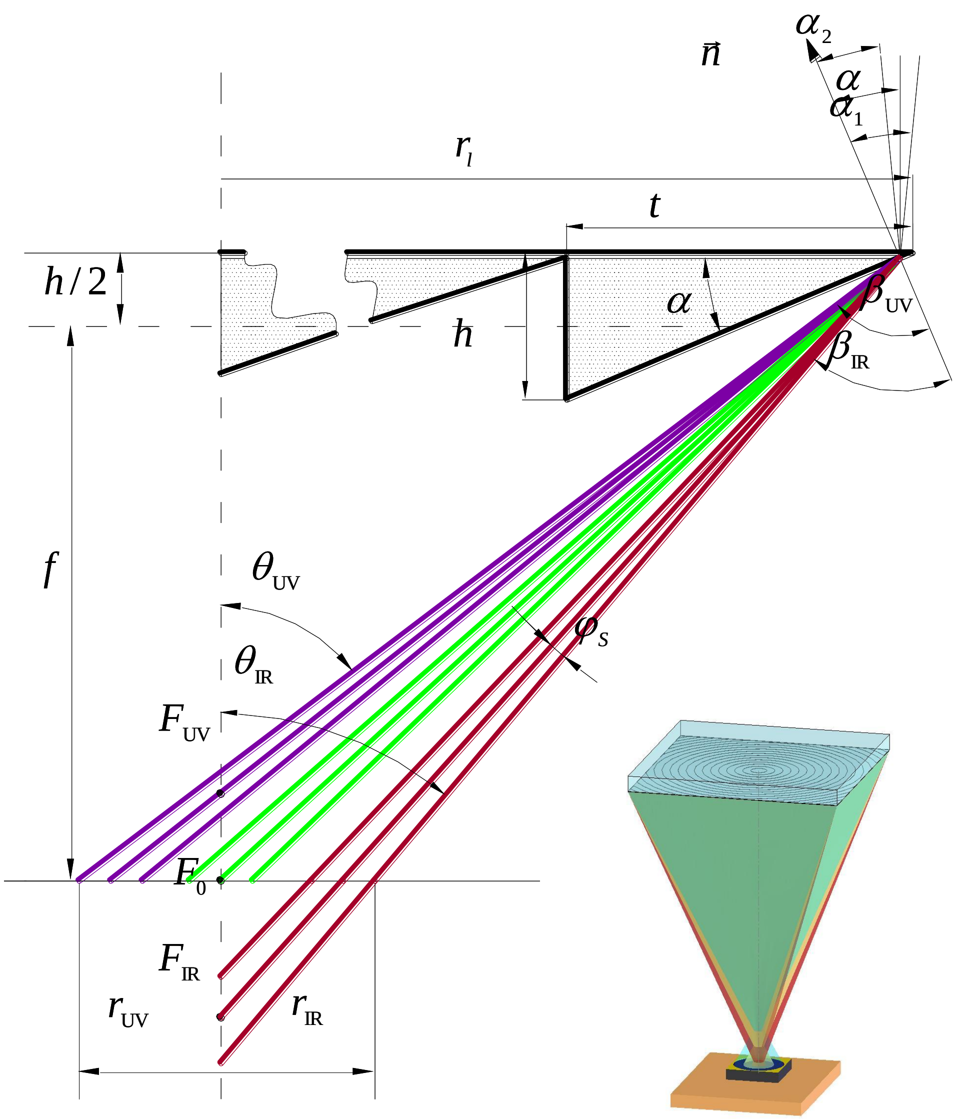


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Diagram of sunlight beam dispersion

$$\alpha = arctg\frac{r_l - t/2}{n_{calc}\cdot\sqrt{(r_l - t/2)^2 + f^2} - f}$$

*Tver'yanovich Eh.V., **"Profiles of solar-engineering Fresnel lenses"**, Applied Solar Energy 1983;19(6), 36–39 [English translation of Geliotekhnika]."*

$$\alpha_1 = \alpha + \varphi_S \qquad \alpha_2 = \alpha - \varphi_S$$

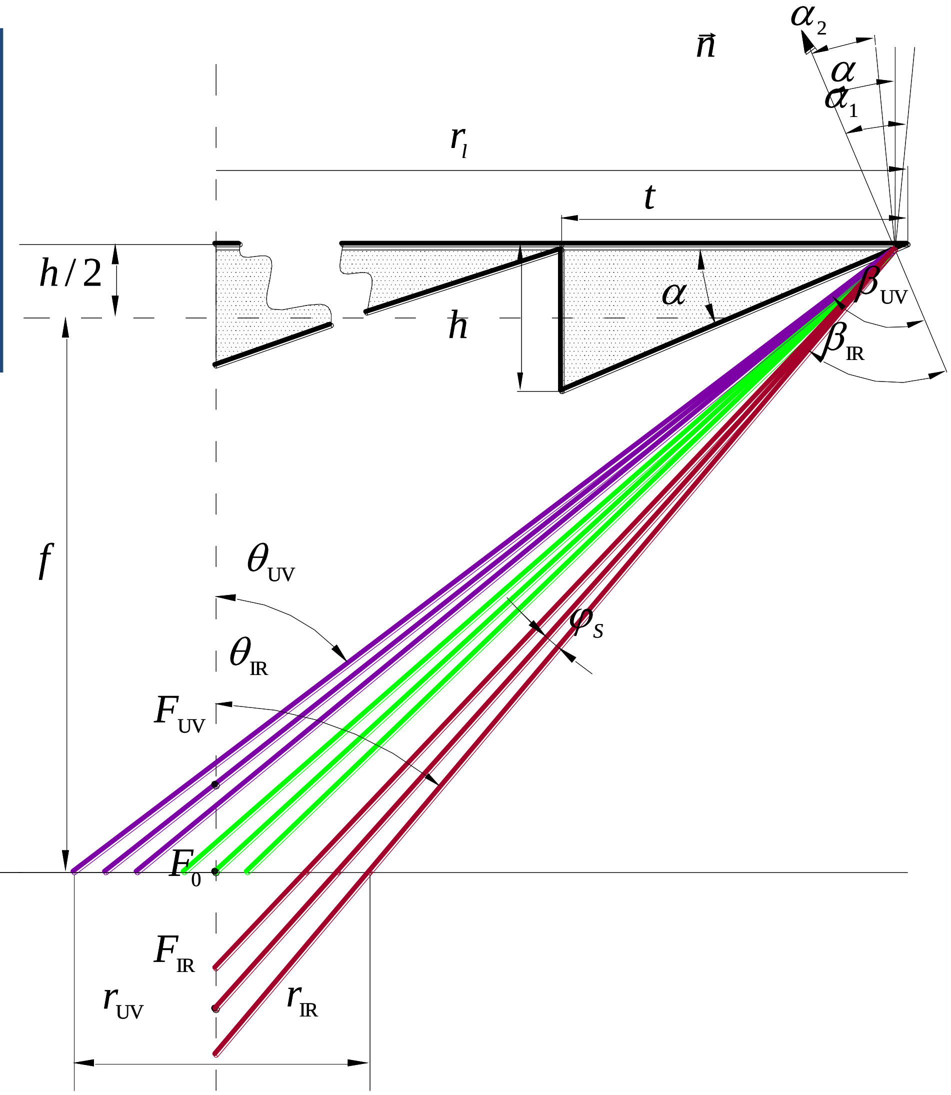
$$\beta_{UV} = \arcsin(n_{UV}\cdot\sin\alpha_1)$$

$$\beta_{IR} = \arcsin(n_{IR}\cdot\sin\alpha_2)$$

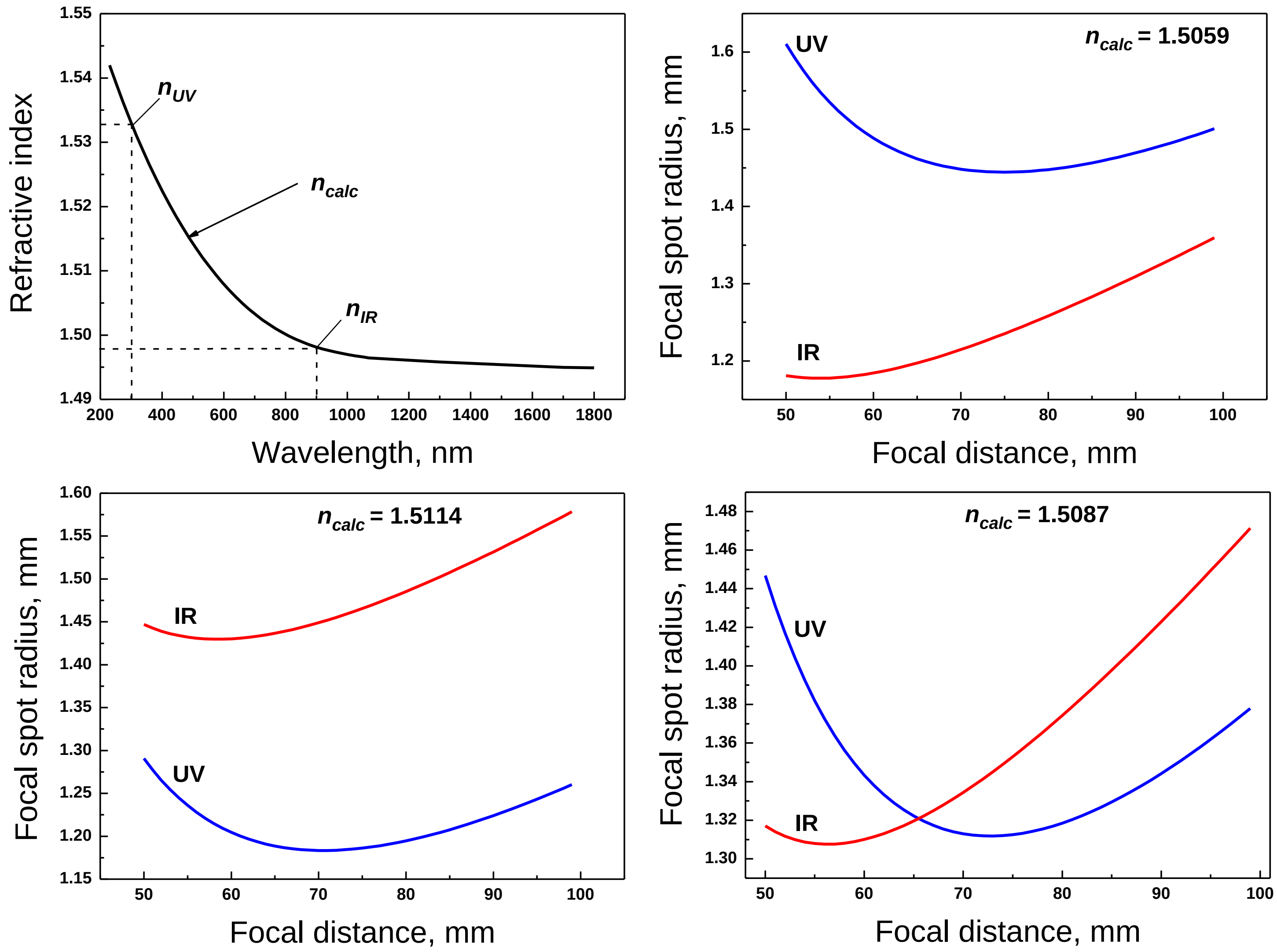
$$\theta_{UV} = \beta_{UV} - \alpha \qquad \theta_{IR} = \beta_{IR} - \alpha$$

$$r_{UV} = (f + h/2)\cdot tg\,\theta_{UV} - r_l$$

$$r_{IR} = r_l - (f + h/2)\cdot tg\,\theta_{IR}$$



The UV and IR spot radii *vs* the focal distance at various n_{calc}



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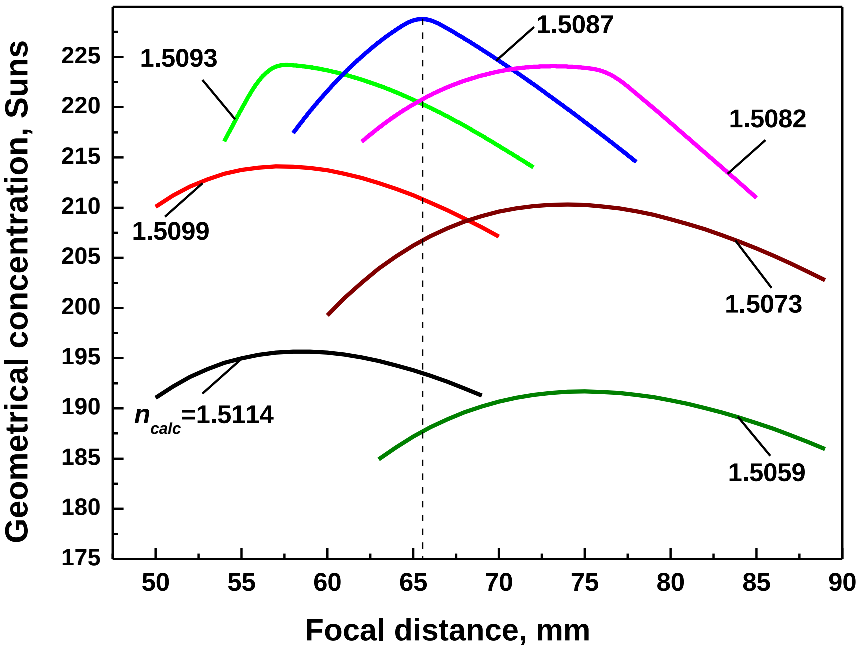
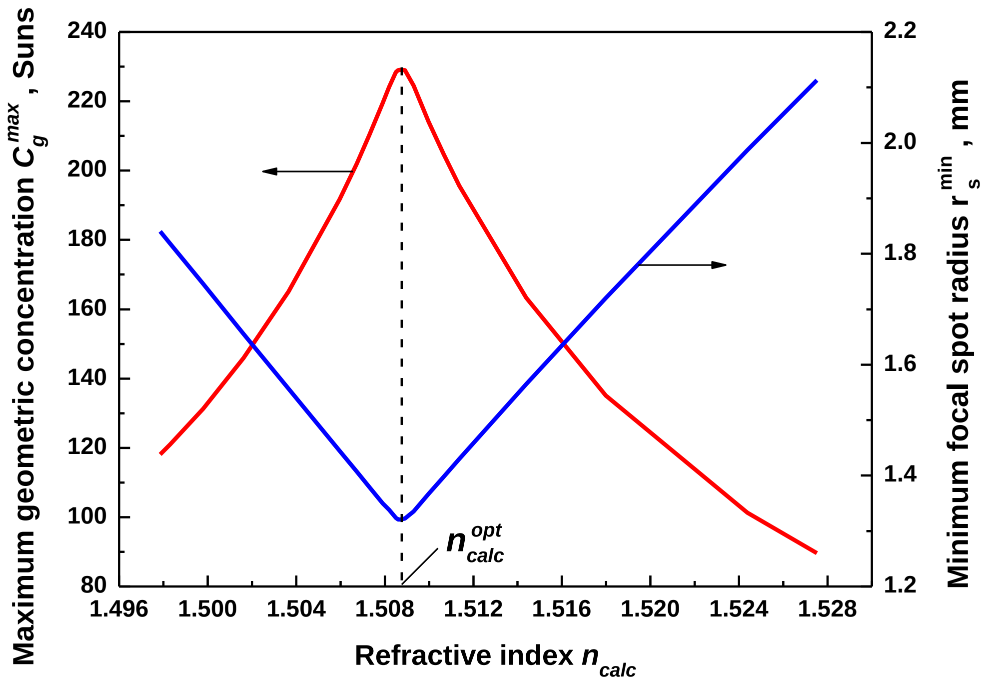
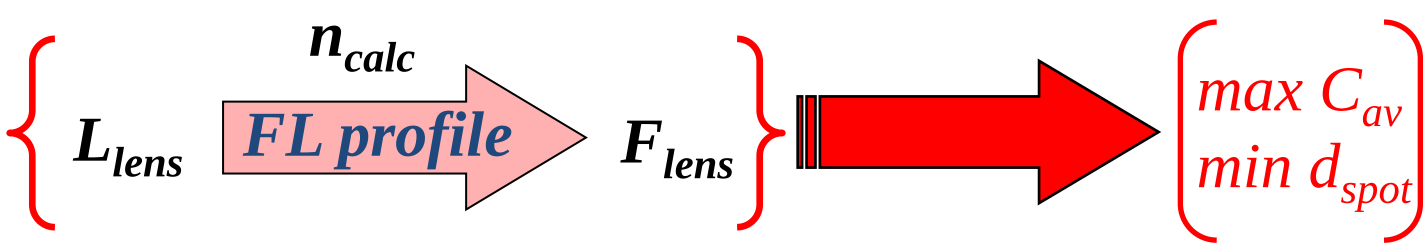
Criteria for Fresnel lens design







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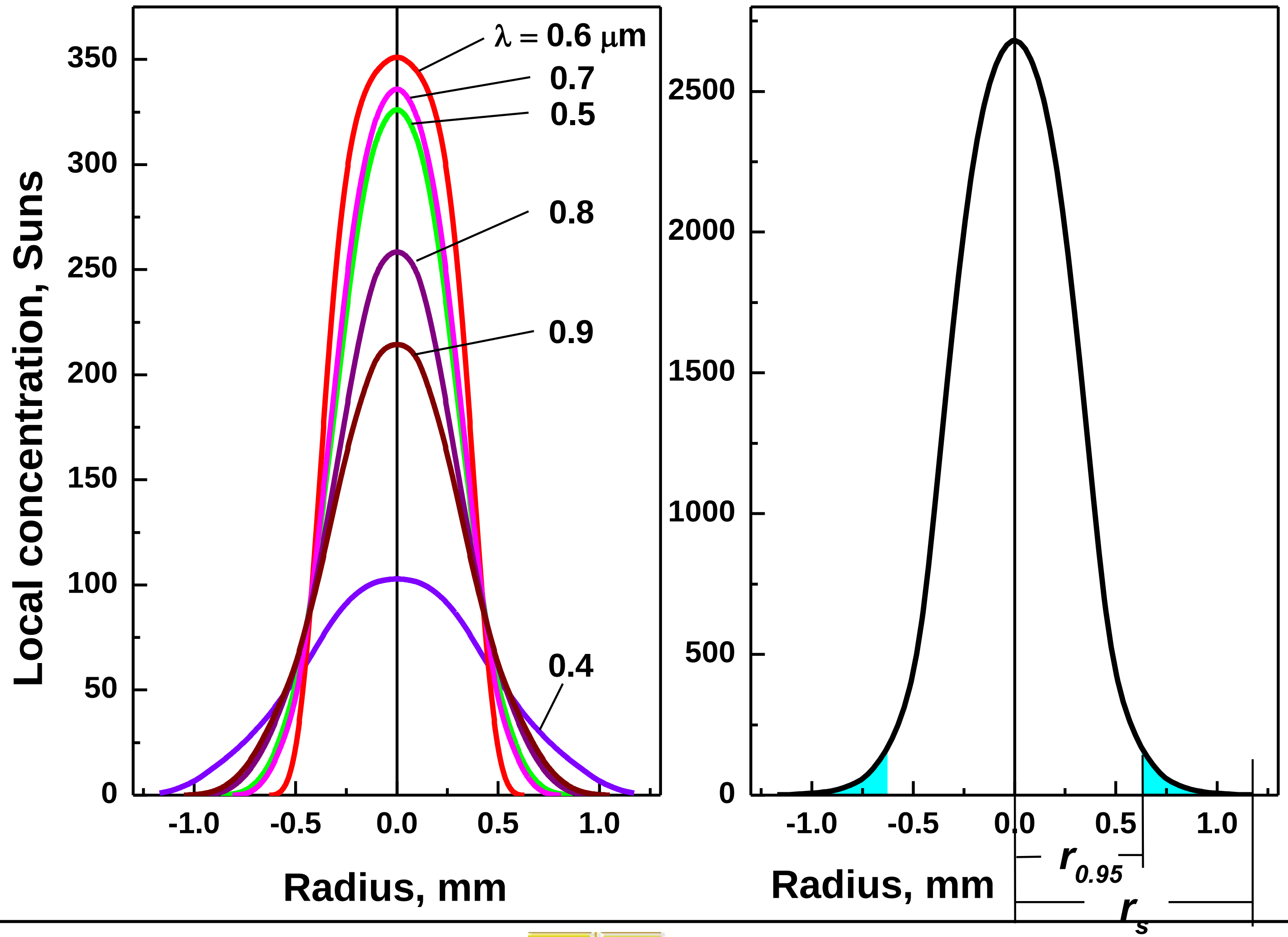
Spectral (left) and integral (right) optical-power characteristics of Fresnel lens



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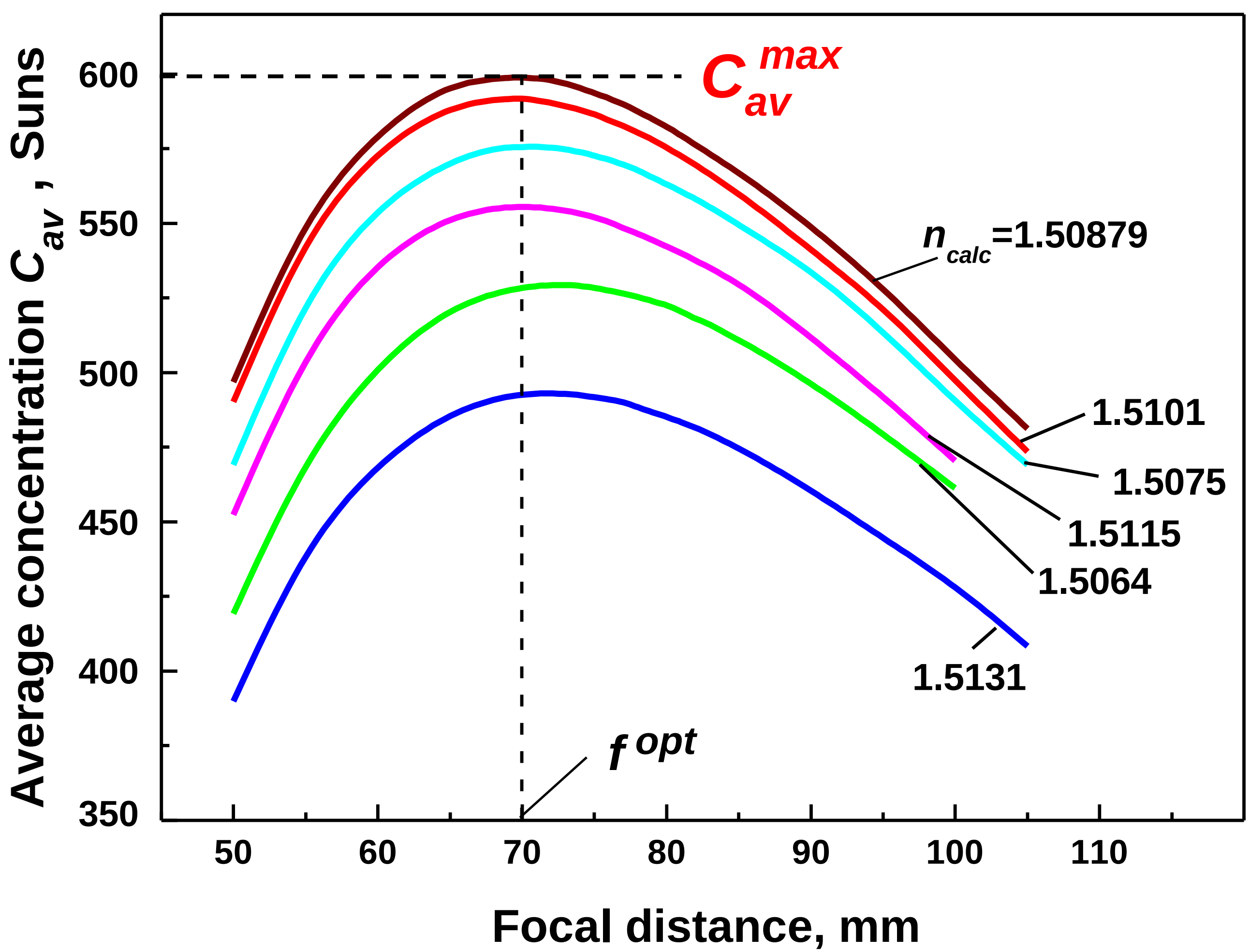
Average concentration ratio *vs* focal distance at different refractive indexes n_{calc} (K_{int} = 0.95)



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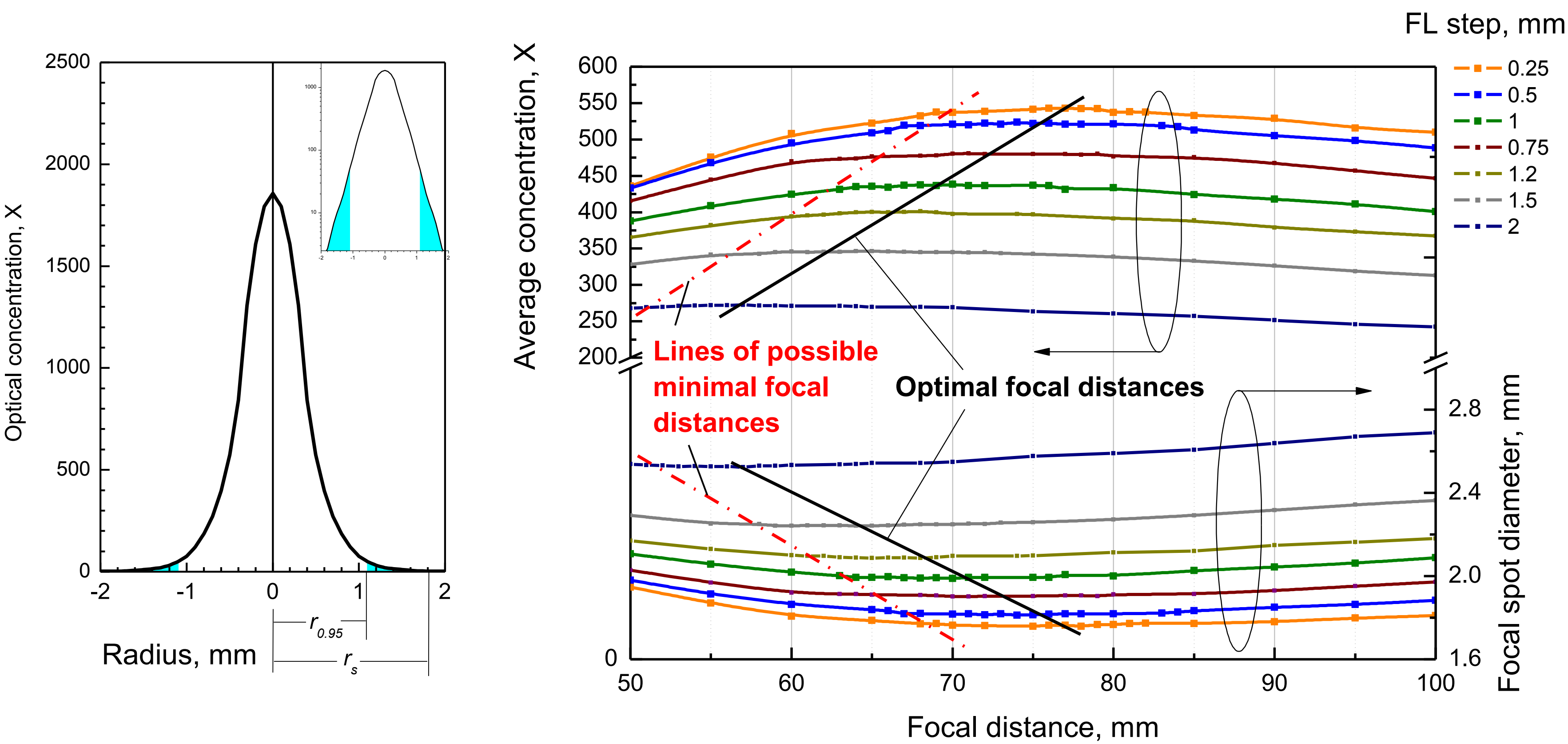
Average concentration ratio *vs* focal distance at different Fresnel profile step (K_{int} = 0.95)



Picks and valley roundness ("dead" zones): 5 mm each ,
refracting surface roughness (mean square error): σ=5 ang. min.

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Diagram of sunlight beam dispersion

$$\alpha = arctg \frac{r_l - t/2}{n_{calc} \cdot \sqrt{(r_l - t/2)^2 + f^2} - f}$$

*Tver'yanovich Eh.V., **"Profiles of solar-engineering Fresnel lenses"**, Applied Solar Energy 1983;19(6), 36–39 [English translation of Geliotekhnika]."*

$$\alpha_1 = \alpha + \varphi_S \qquad \alpha_2 = \alpha - \varphi_S$$

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$$\beta_{IR} = \arcsin(n_{IR} \cdot \sin\alpha_2)$$

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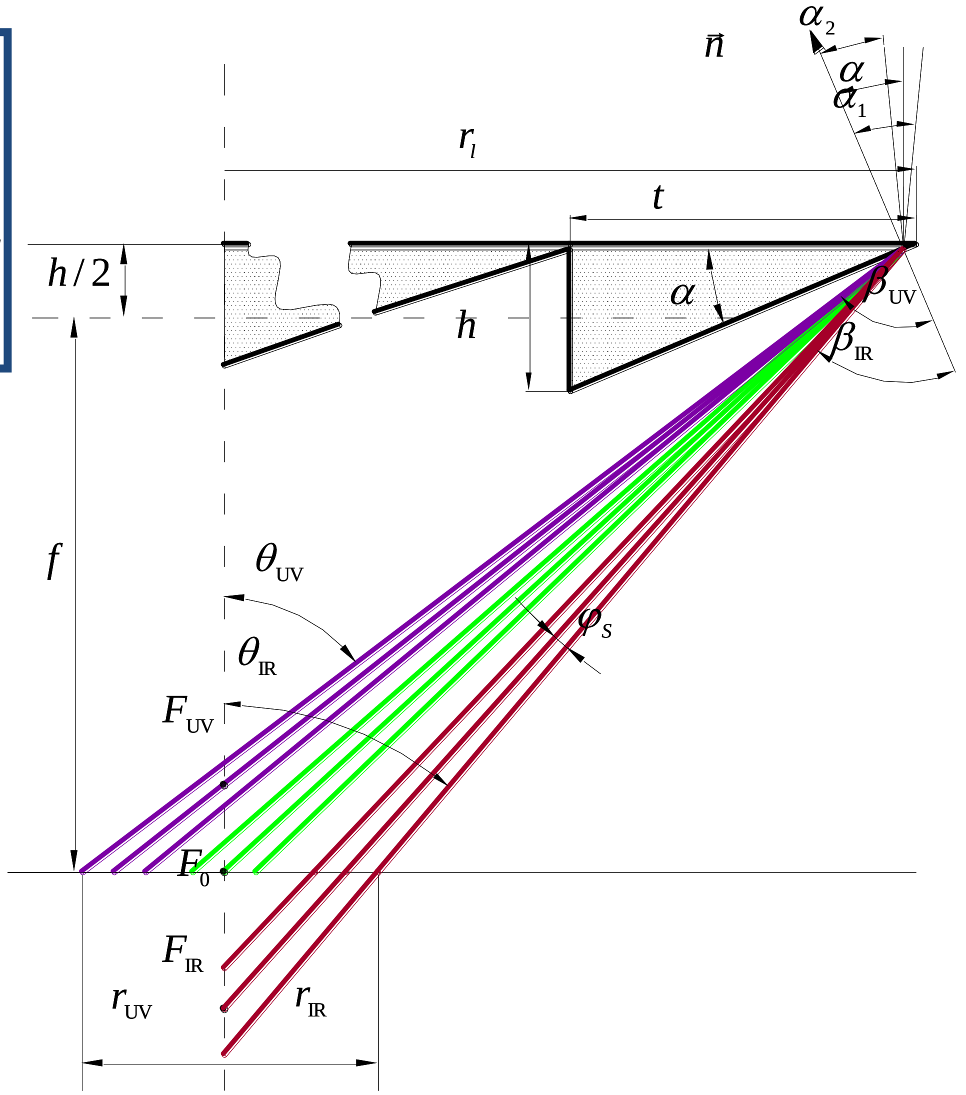
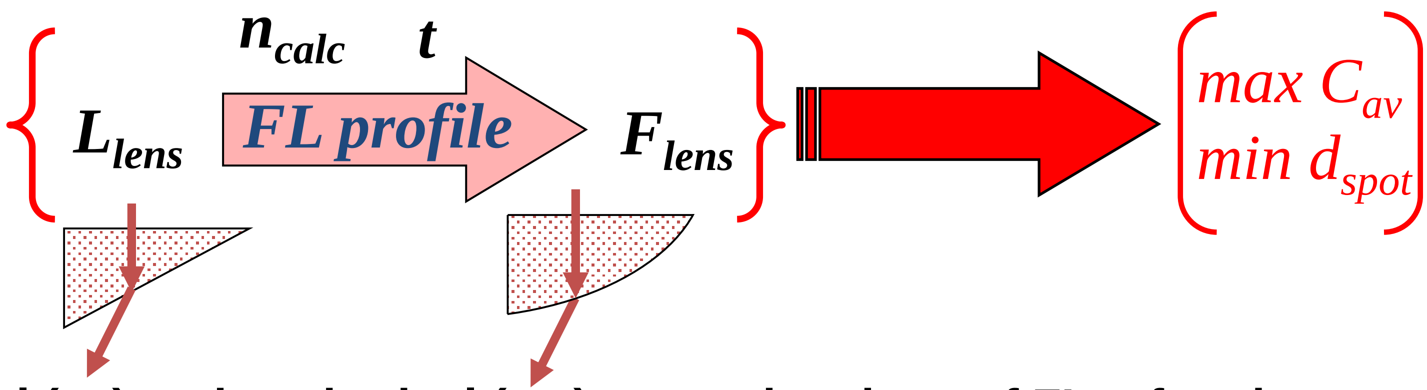
$$r_{UV} = (f + h/2) \cdot tg\,\theta_{UV} - r_l$$

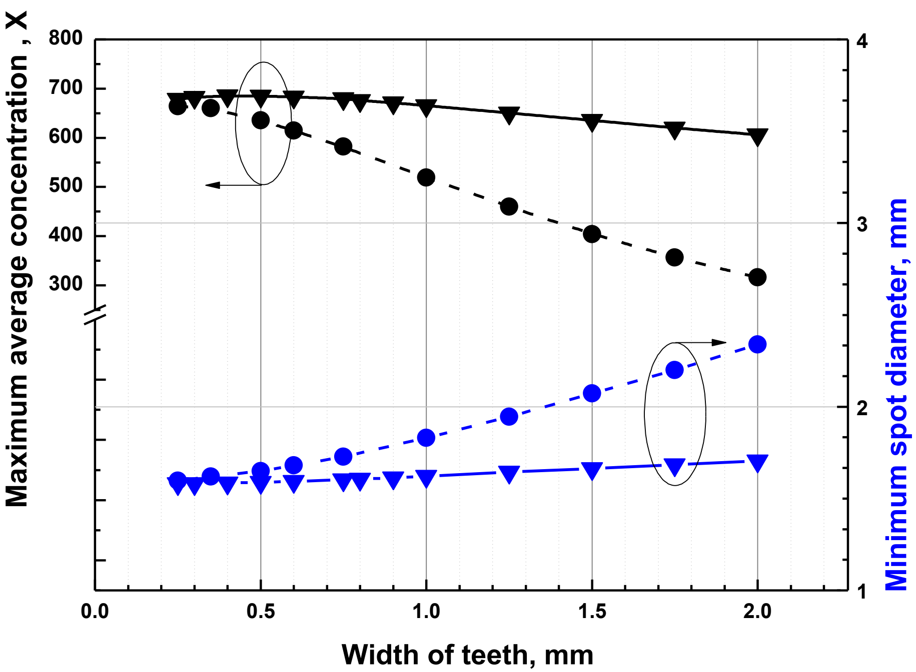
$$r_{IR} = r_l - (f + h/2) \cdot tg\,\theta_{IR}$$

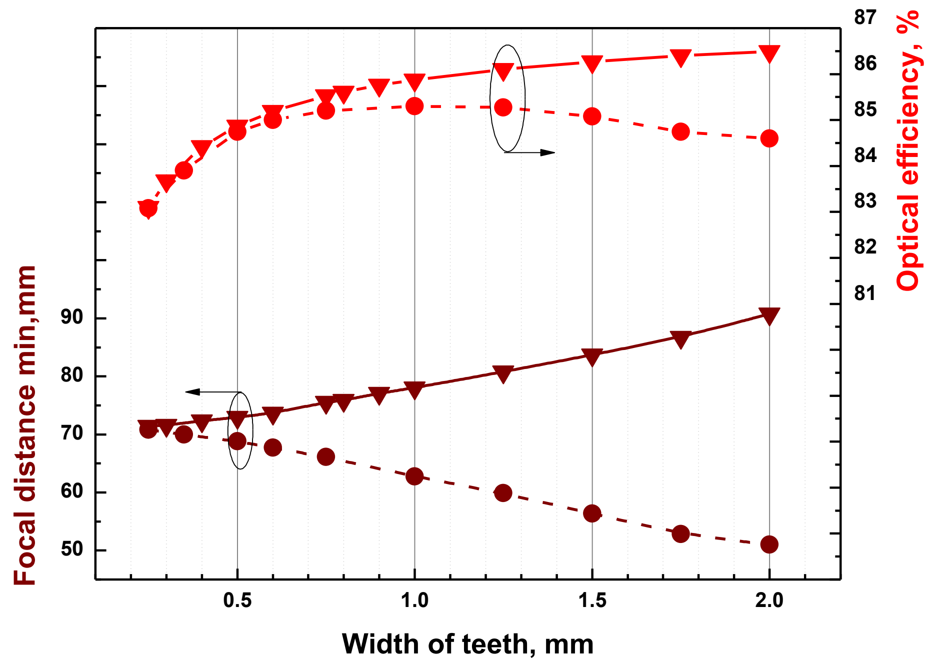


Comparison of optical parameters for FLs



Conical (●) and aspherical (▼) approximations of FL refractive contours





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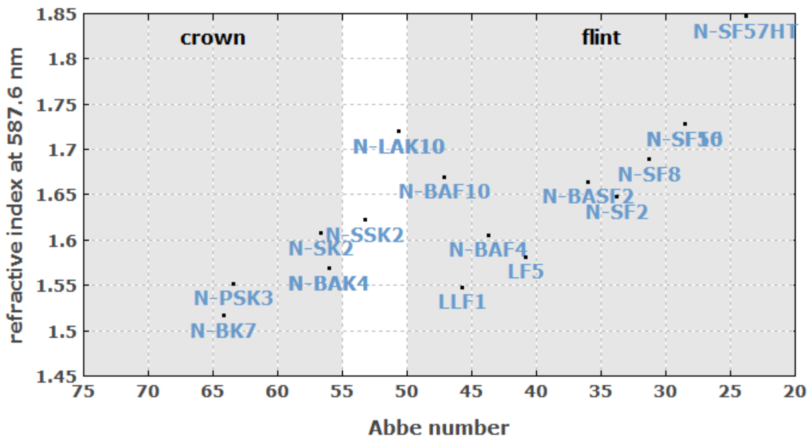
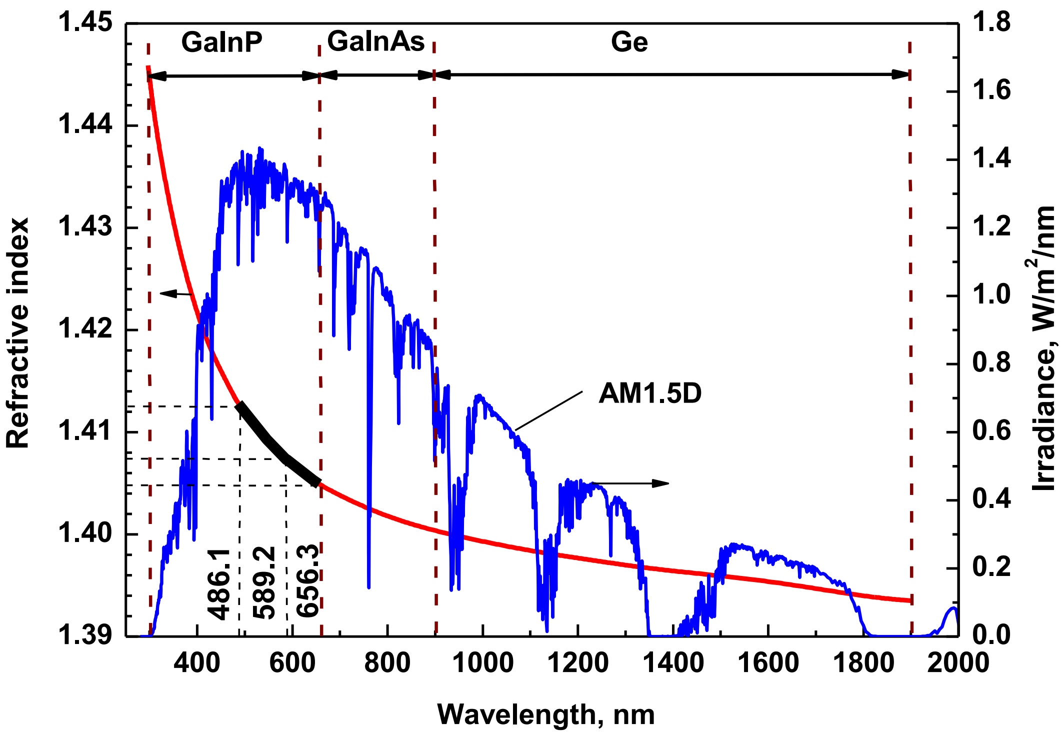
Abbe number – a measure of chromatic dispersion of a transparent material

$$\textit{Abbe number}\ (\nu) = \frac{n_D - 1}{n_F - n_C}$$

(optical dispersion)

589.2 nm → n_D; 486.1nm → n_F; 656.3 nm → n_C





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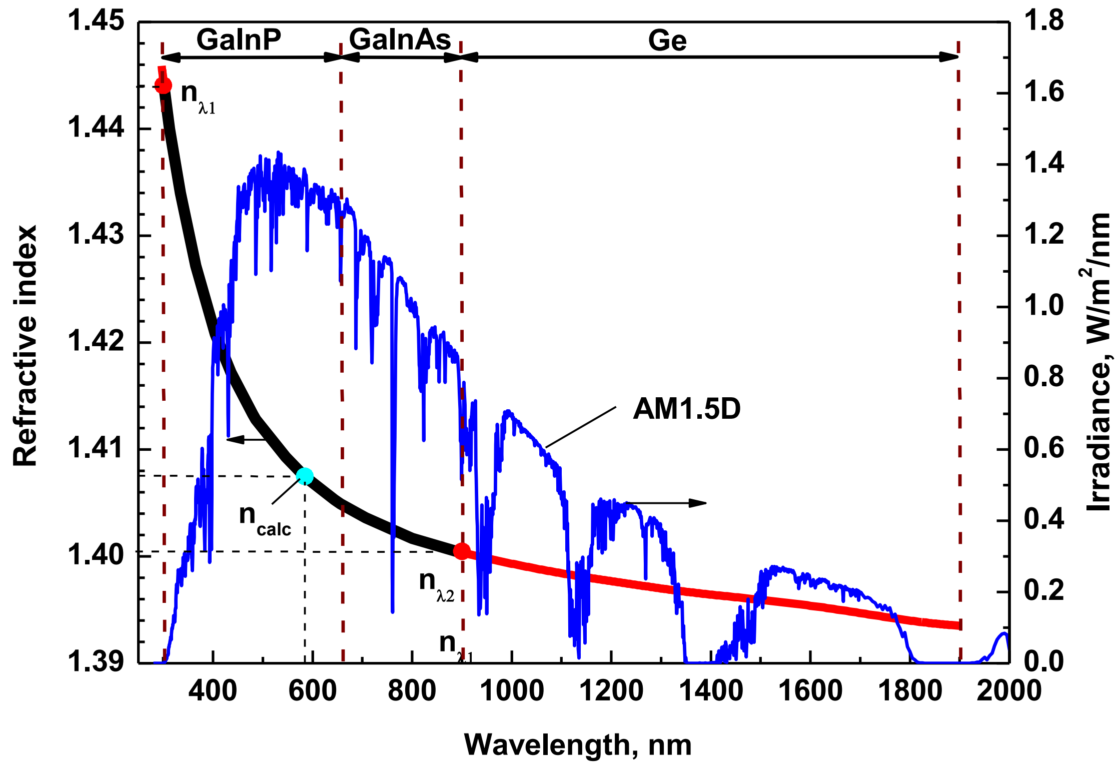
"Solar" Abbe number
as an indicator of the "effectiveness" of the optical material

$$\text{"Solar" Abbe number } (\nu) = \frac{n_{calc} - 1}{n_{\lambda 1} - n_{\lambda 2}}$$



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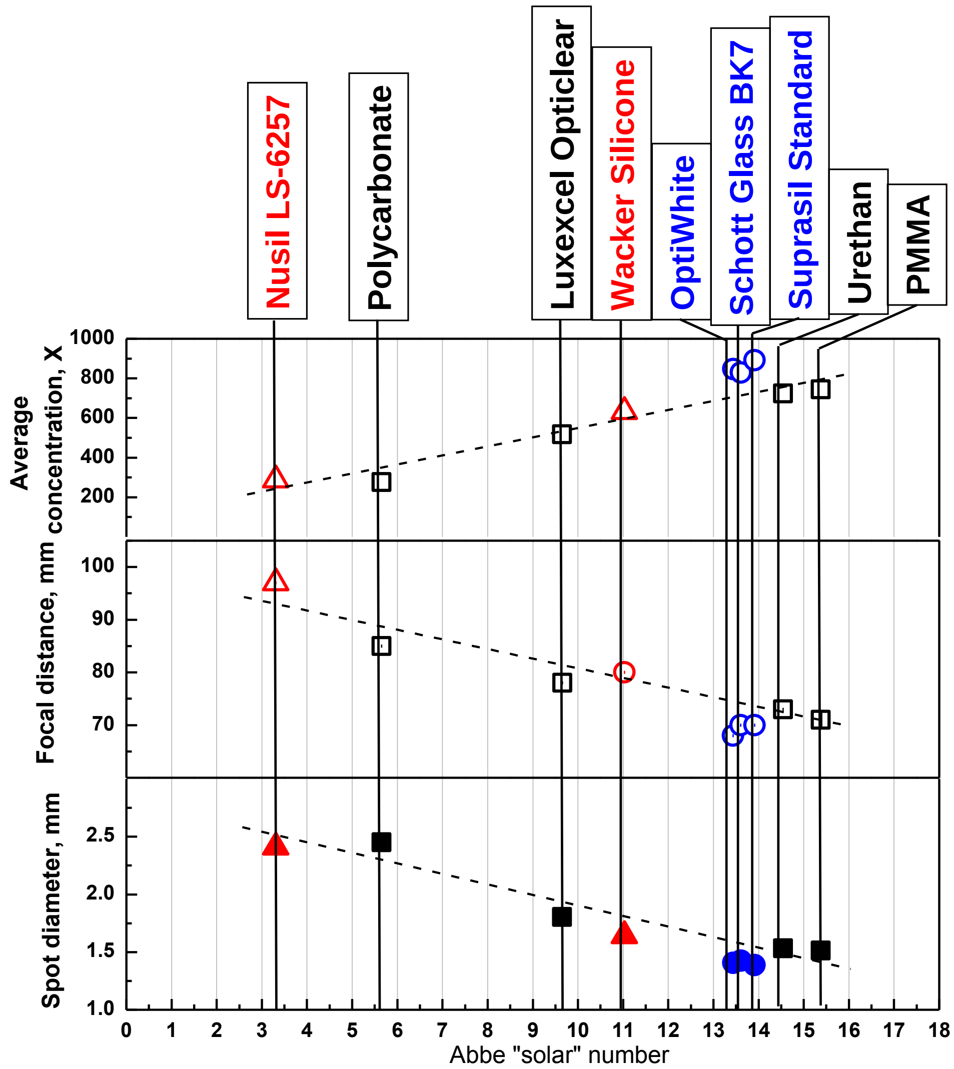
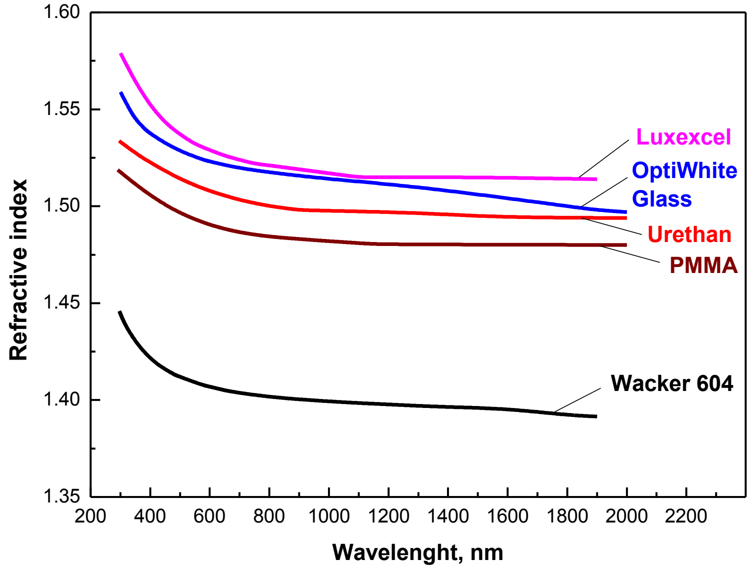
“Solar” Abbe number of the lens material as an indicator of the “effectiveness” of the optical material



$$\nu = (n_{calc}-1)/(n_{\lambda 1} - n_{\lambda 2})$$



Size a_{lens} **= 40 mm,**
Profile step t **= 0.25 mm**
K_{int}**=0.95** **σ= 5 '**
Width of the rounding zones: tops/valleys - 5 µm

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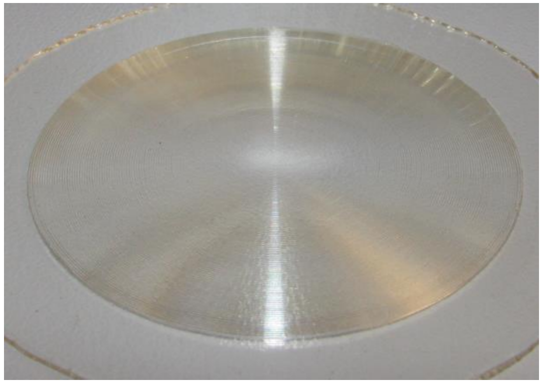
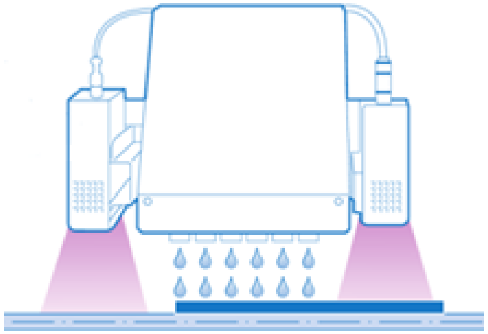
Fresnel lens manufacturing

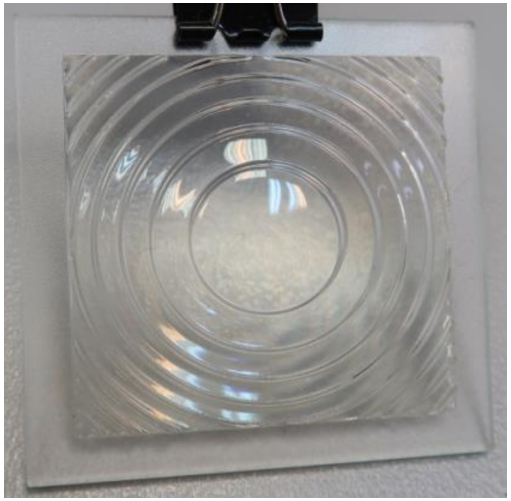
Negative mold: diamond cutting technique

Silicone-on-glass replication or injection molding for plastics



3D additive technology





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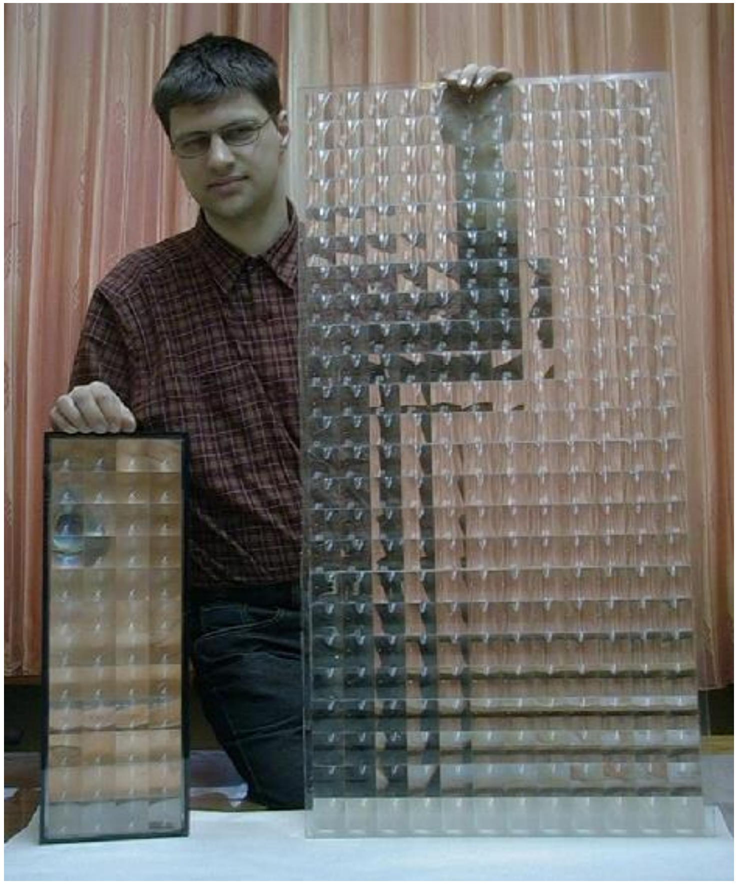
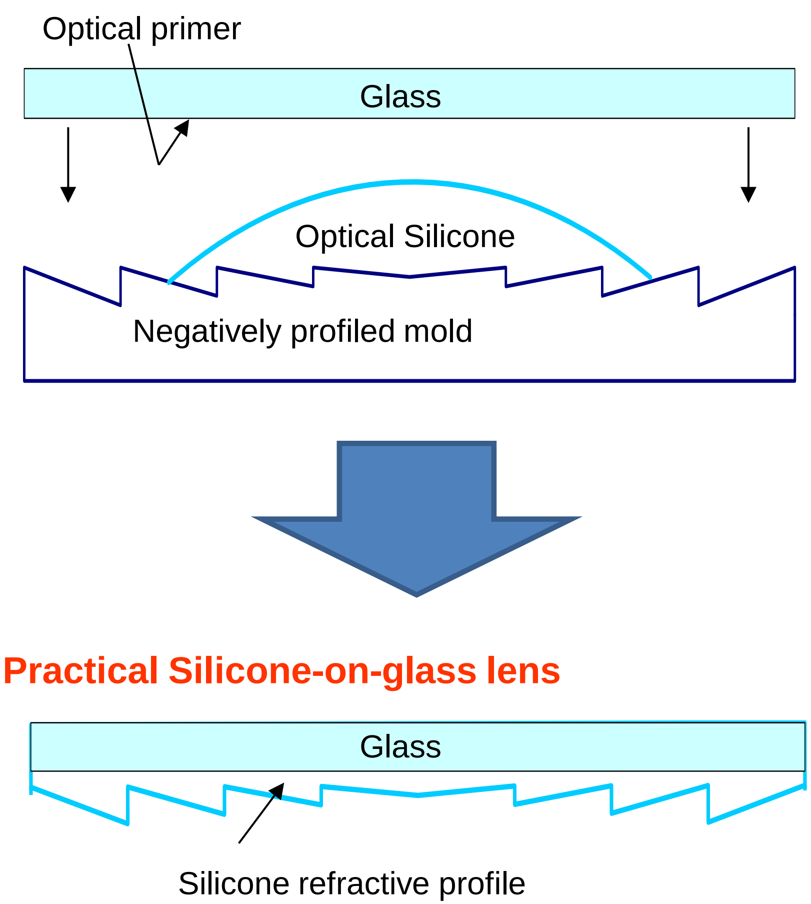
Silicone-on-glass Fresnel lenses

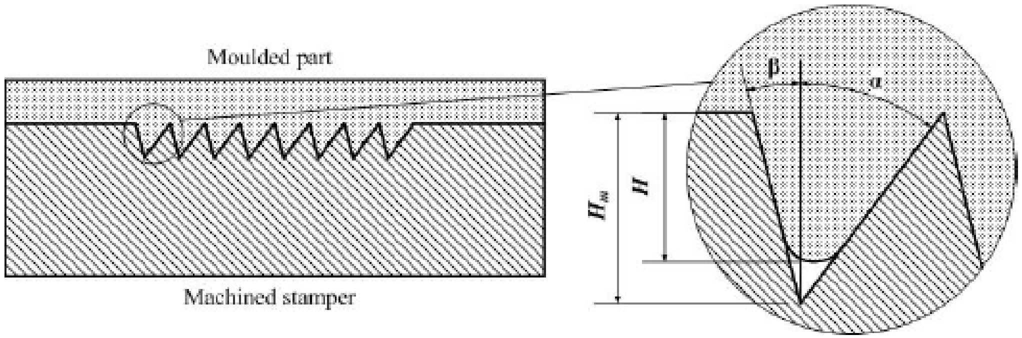


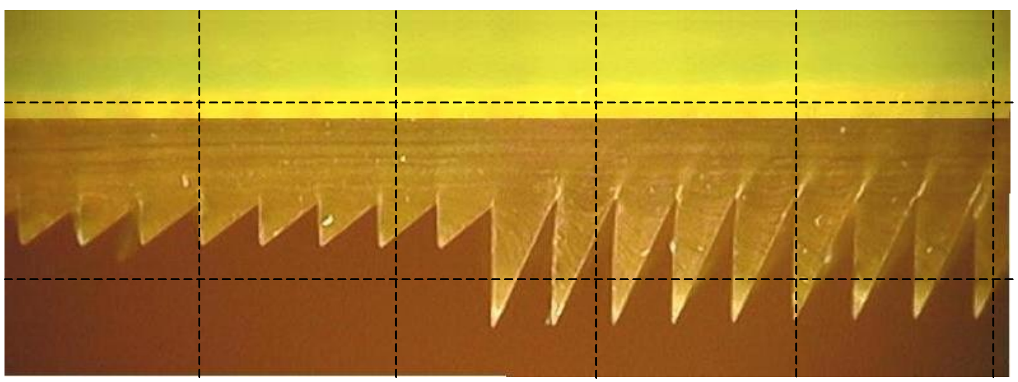
SoG Lens Panel

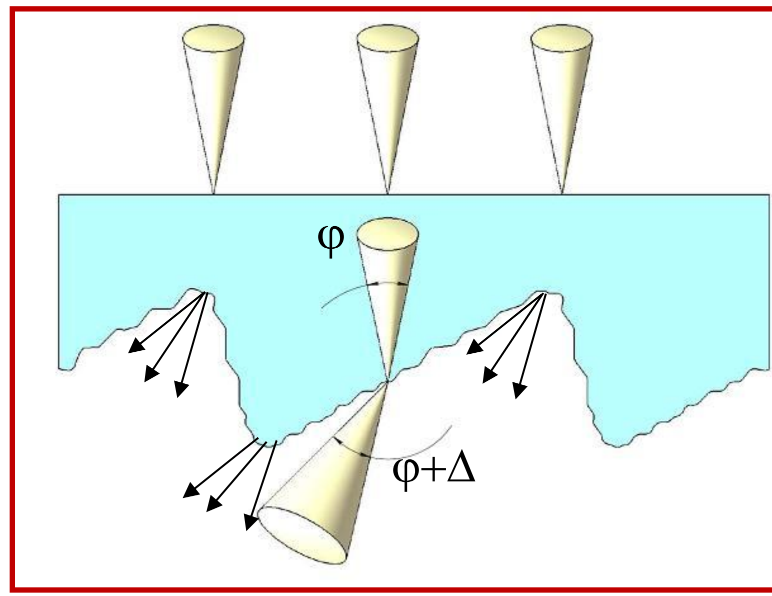


Possible geometrical imperfections to be considered in ray-tracing model

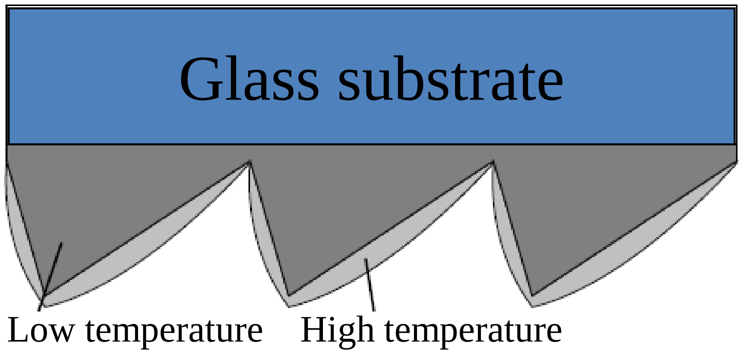
- deviation of the tooth tilt angles (σ);
- refracting surface roughness;
- roundness of tooth peaks and grooves.



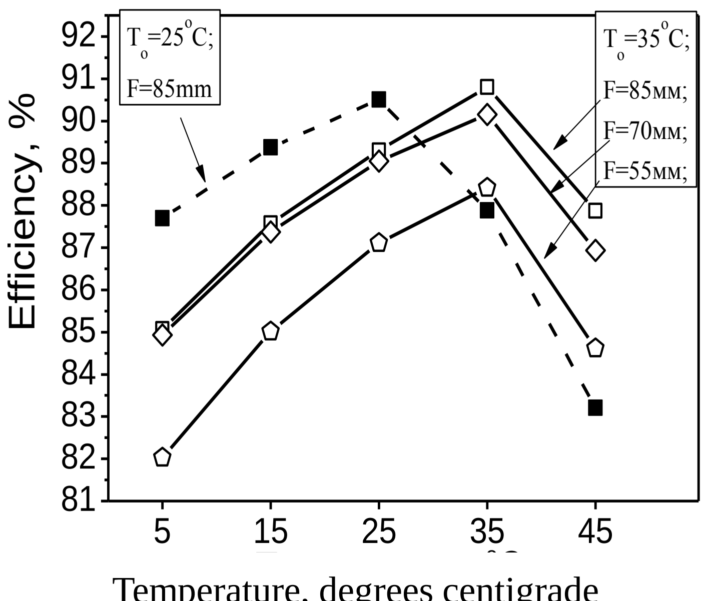


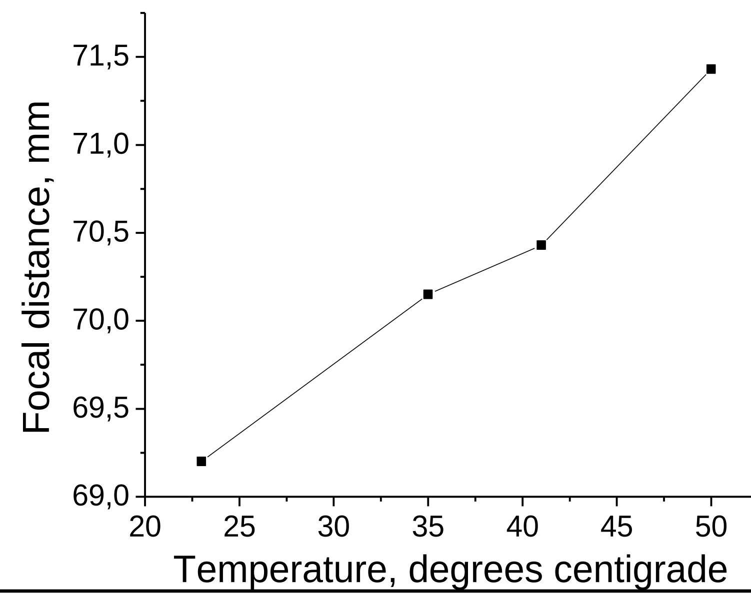


Deformation of the silicone microprisms due to difference in thermal expansion coefficients of glass and silicone



Schematic visualization of thermal deformations of Fresnel lens prisms on a glass substrate when the temperature is increased. Deformations are strongly exaggerated; real scale deformations would not be distinguishable from the original structure in this picture and resolution. In a CPV module the top side of this picture would be facing the sun; the lens structure is inside the module.





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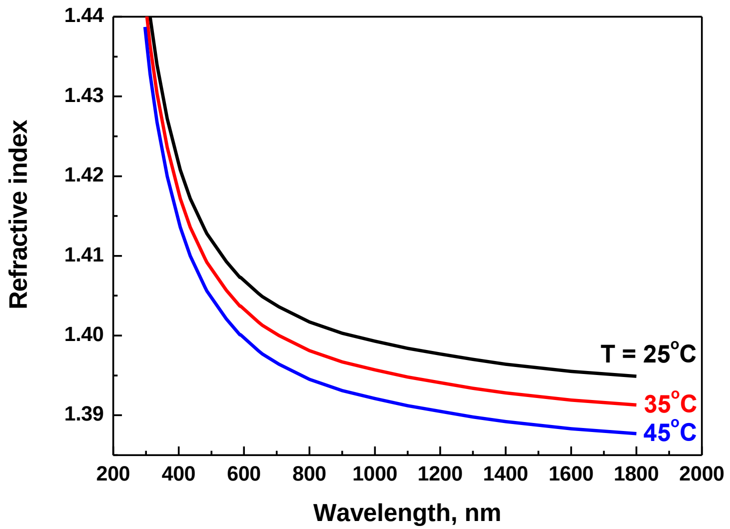
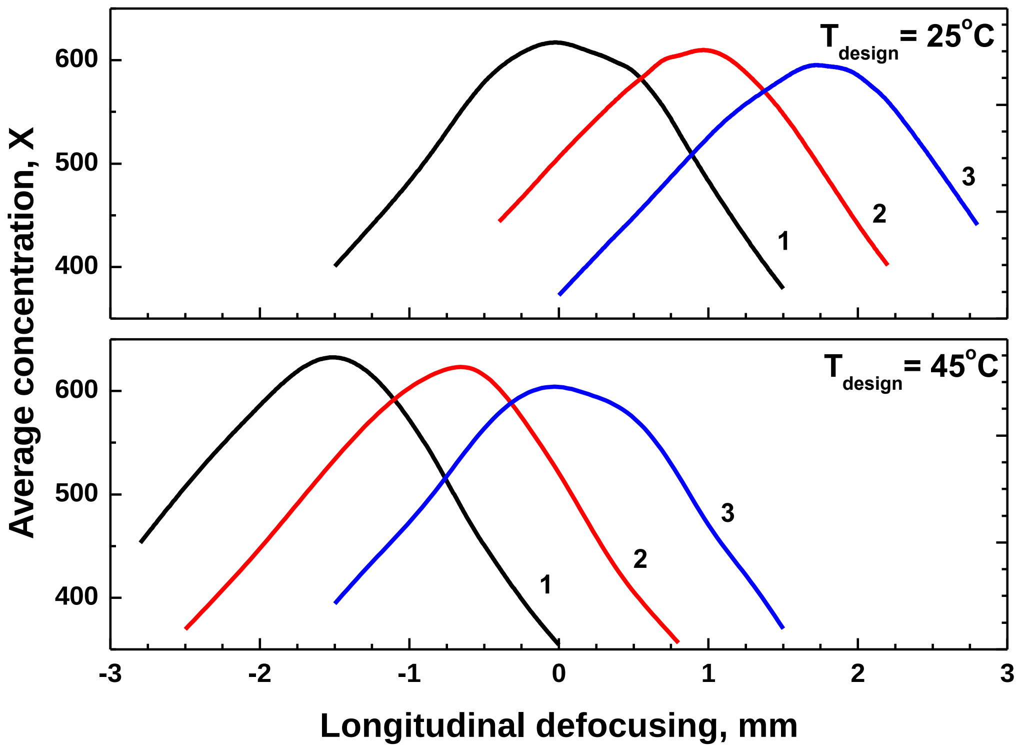
Temperature effect on Fresnel lens concentration capability





Dependencies of the average concentration ratio in the spot (K_{int}=0,95) on the longitudinal defocusing at different lens operating temperatures.
The lens operating temperatures, °C: 1 – 25; 2 – 35; 3 – 45.

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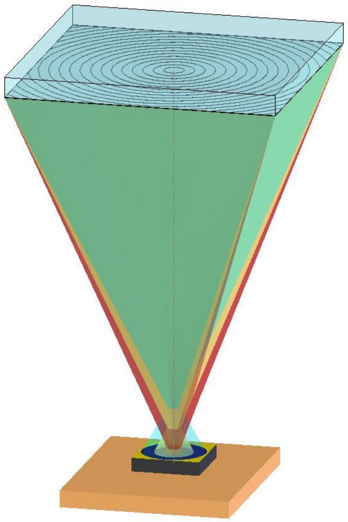
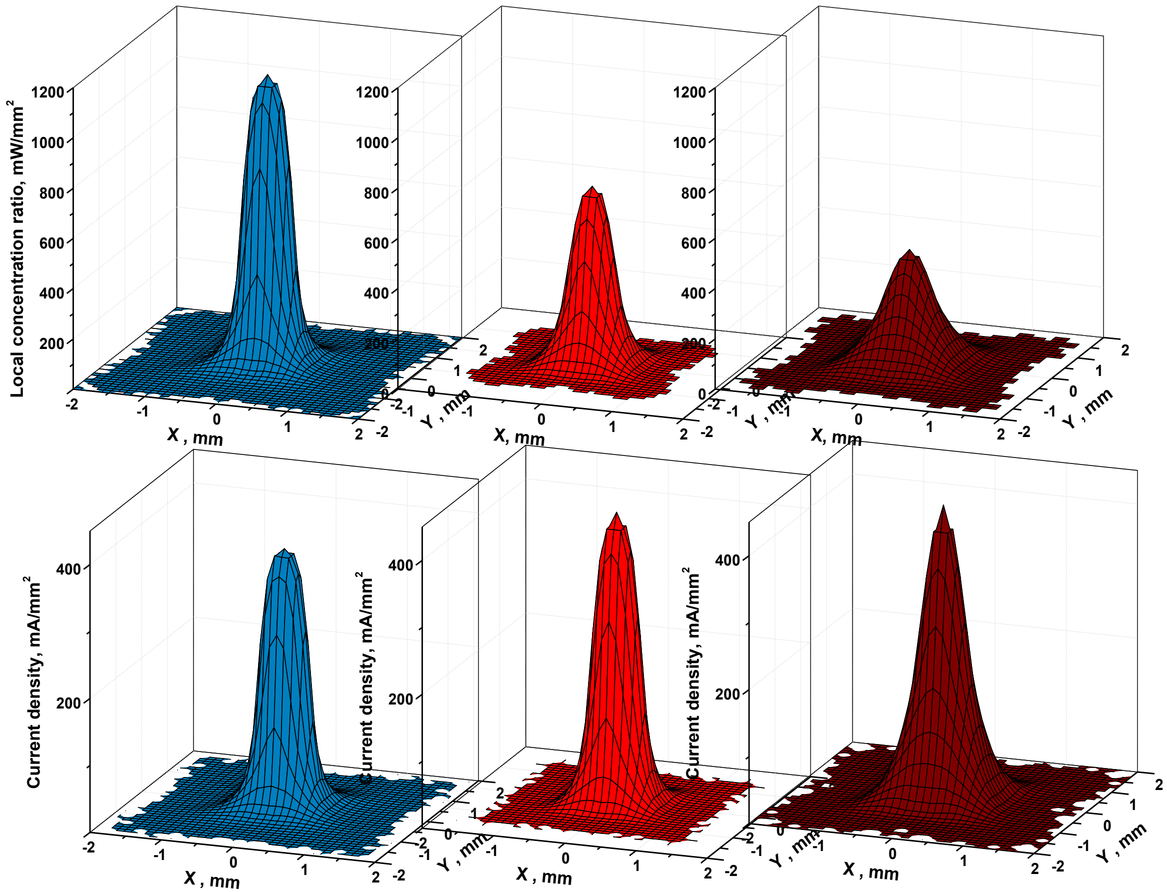
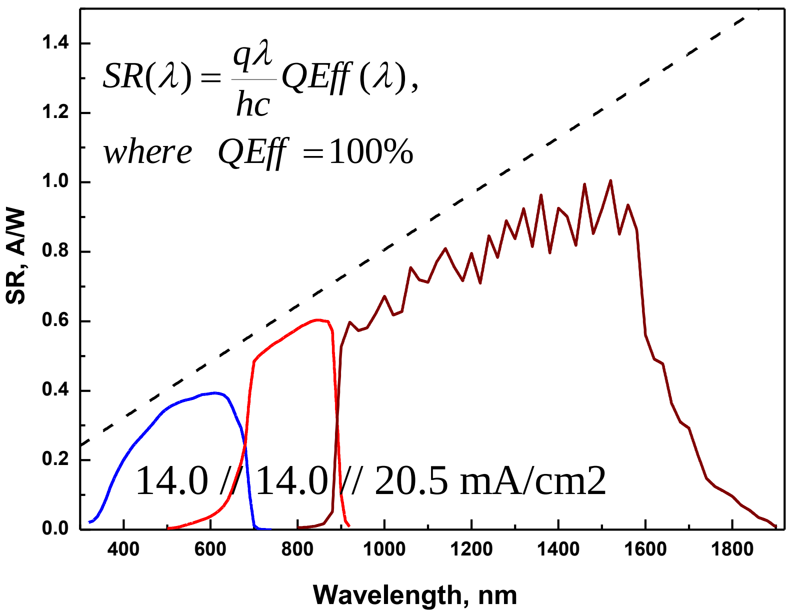
Distributions of concentrated power and corresponded to them distributions of photocurrent densities for p-n junctions of TJ SC

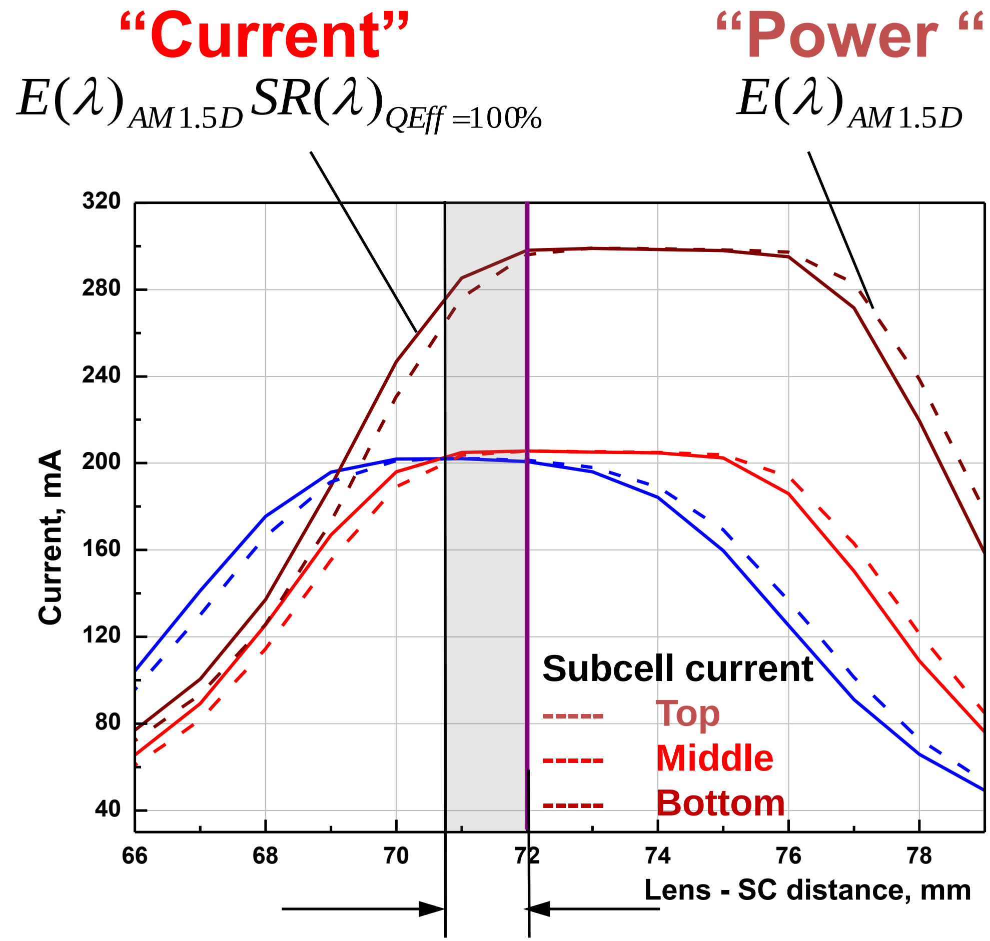


Top **Middle** **Bottom** **subcells**



FL design: Comparison of “Power” and “Current” concepts





Possible room for
“FL-SC” distance tuning

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Conclusion

- Criteria of FL optimization to achieve maximum average concentration and optical efficiency
- Correlations between construction and optical parameters
- Efficient materials for FL manufacturing and it estimations with use of Abbe “solar” number
- Temperature effect on FL concentration capability
- FL tuning for best matching with MJ SC