

Opti 521/421 Tutorial for Plastic Optical Materials

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1. Introduction

Plastics optical materials have plenty of applications in consumer products. The main reason for the use of plastic optics is *cost*. The other benefits from using plastic optical materials are production volume, integral features, weight reduction, and aspheric or diffractive surfaces. Though these polymers have issues on lower service temperature than glass, high dn/dT and CTE, environmental susceptibility, high birefringence, and limited material selection, several consumer markets still get the advantage of high-volume/low-cost production in plastic optics.

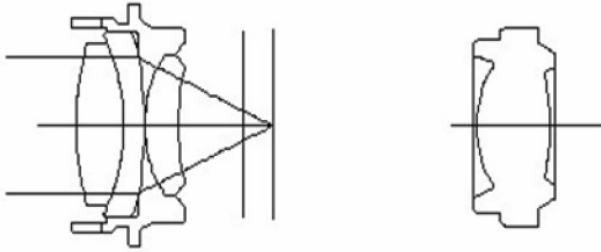
In this tutorial report we first discussed the material properties of plastic optical materials due to effect dimensional stability of a plastic component, then summarized the merit to build up a wavefront error budget for plastic optics. In the end of tutorial, several common used plastic optical materials are listed and discussed. The notable characteristics of these materials could be considered while designing.

2. Material Properties

The use of plastic optical elements is good for reduction of weight due to relatively smaller densities. General densities of plastic optical materials are about 1 g/cm^3 . This excellent property get a huge advantage while the system used plastic optical elements with integrated configuration instead of general optical system composed by image elements and assembly barrel (see Fig 1 and Fig 2), which replaced large amount of weight materials to weightless polymers.

On the other hand, some material properties of plastic optical materials are poor and come out several optomechanical challenges. The weakness of strength in polymers (Young's modulus of plastic optical materials are in the range of 1~3 GPa) would result the ease of deflection by external loading or intrinsic mass. Also, the high coefficients of thermal expansion CTE (about 10 times larger than glass) would result sensitive thermal distortion by either steady-state or transient temperature environment. These material properties introduce the dimensional instability for plastic optical elements.

Figure 1. Edge configuration of a focusing system



Left: original design combination which composed by lenses and barrel; right: an aspheric plastic optical element which can be used to replace original design and reduce system weight

Figure 2. Monolithic plastic optical assembly made of PMMA



Table 1. Material properties for a typical plastic optical material PMMA

| Optical Materials | Density ρ | Young's Modulus E | Refractive Index Change per Degree dn/dT | Coefficient of Thermal Expansion CTE α | Thermal Conductivity λ |
|-------------------------------------|-------------------|------------------------|--|--|--------------------------------------|
| unit | g/cm^3 | GPa | ppm/ $^{\circ}C$ | ppm/ $^{\circ}C$ | W/mK |
| Poly(methyl methacrylate) (PMMA) | 1.16 | 3 | -8.5 | 72 | 0.21 |
| BK7 | 2.51 | 82 | 1.86 | 7.1 | 1.1 |
| Aluminum | 2.68 | 68 | | 23.6 | 170 |

2.1 Structural Stability

Followed the Opti 521/421 class discussion, the higher the resonant frequency of a certain component, the stiffer it is. The further the resonant frequency is from the excitation frequency, the smaller is the oscillation amplitude. The angular resonant frequency ω of a component is presented by stiffness k and its mass:

$$\omega = \sqrt{\frac{k}{m}}$$

For a homogeneous beam with regular cross-section, the stiffness and mass are determined:

$$k = \frac{EI}{l^3} = \frac{E}{l^3} \cdot \frac{bh^3}{12}; \quad m = \rho bhl$$

where E is Young's modulus, l is the length, b is the width, h is the height of the beam, and I is the geometrical moment of inertia. Substituting these expressions in the angular resonant frequency it is given:

$$\omega = \frac{h}{2\sqrt{3}l^3} \cdot \sqrt{\frac{E}{\rho}}$$

The assumption shows in constant geometry the resonant frequency is proportional to square root of the ratio E/ρ . To have good structural stability, the ratio should be as large as possible.

The other representing ratios are ρ/E for *deflection at constant thickness*, ρ^3/E for *deflection at constant mass*, and square root of ρ^3/E for *mass at constant deflection* of a certain component. Contrary to the resonant frequency figure of merit, here one prefers the ratios as low as possible to minimize deflection. Some selected plastic optical materials with structural properties are listed in Table 2.

Table 2. Structural properties and figures of merit for plastic optical materials

| property, figure of merit | | | density, ρ | Young's modulus, E | intrinsic birefringence, $\Delta n_0\alpha$ | photo- elastic coefficient | $\sqrt{E/\rho}$ | ρ/E | ρ^3/E | $\sqrt{(\rho^3/E)}$ |
|------------------------------------|---------|--------------------|--------------------|----------------------------|---|----------------------------------|-----------------------------------|------------------------------|-------------------------|---------------------------|
| compares | | | | | | | resonant frequency geometry | deflection thickness | deflection mass | mass thickness |
| constant independent variable | | | | | | | $10^{-8}/\text{MPa}$ | $(10^6 \text{ Nm/kg})^{0.5}$ | 10^{-6} kg/Nm | kg^3/Nm^7 |
| unit | | | g/cm^3 | GPa | – | | large | small | small | small |
| preferred | | | small | large | small | | | | | |
| material | abbrev. | trade name | | | | | | | | |
| cyclic olefin copolymer | COC | Topas | 1.02 | 3.1 | | | 1.73 | 0.33 | 0.35 | 0.59 |
| cycloolefin polymer | COP | Zeonex, Zeonor | 1.01 | 2.2 | | 6.5 | 1.46 | 0.47 | 0.48 | 0.69 |
| polycarbonate | PC | Makrolon, Lexan | 1.2 | 2.4 | 0.106 | 72 | 1.41 | 0.50 | 0.72 | 0.85 |
| poly(methyl methacrylate) | PMMA | Plexiglas | 1.16 | 3 | -0.0043 | -6 | 1.59 | 0.40 | 0.56 | 0.75 |
| polystyrene | PS | Styron | 1.05 | 2.89 | -0.1 | -55 | 1.66 | 0.36 | 0.40 | 0.63 |
| allyl diglycol carbonate | | CR39 | 1.31 | 3 | | | 1.51 | 0.44 | 0.75 | 0.87 |
| poly(styrene- co-acrylonitrile) | SAN | | 1.07 | 3.3 | | | 1.76 | 0.32 | 0.37 | 0.61 |
| poly(styrene- co-methacrylate) | NAS | | 1.14 | 2.34 | | | 1.43 | 0.49 | 0.63 | 0.80 |
| poly(4-methyl- 1-pentene) | PMP | TPX | 0.833 | 1.28 | | | 1.24 | 0.65 | 0.45 | 0.67 |
| amorphous nylon | | Grilamid TR90 | 1.183 | 1.6 | | | 1.16 | 0.74 | 1.03 | 1.02 |
| poly(ether sulfone) | PSU | Udel | 1.24 | 2.48 | | | 1.41 | 0.50 | 0.77 | 0.88 |
| poly(ether imide) | PEI | Ultem | 1.27 | 3 | | | 1.54 | 0.42 | 0.68 | 0.83 |
| N-BK7 | | | 2.51 | 82 | | | 5.72 | 0.03 | 0.19 | 0.44 |
| Germanium | | | 5.33 | 102.7 | | | 4.39 | 0.05 | 1.47 | 1.21 |
| Sapphire | | | 3.97 | 335 | | | 9.19 | 0.01 | 0.19 | 0.43 |
| SF57 | | | 5.51 | 54 | | | 3.13 | 0.10 | 3.10 | 1.76 |

From *Hand Book of Plastic Optics* and Opti 521/421 Prof. Burge Class Note

2.2 Thermal Stability

Assuming a constant heat flux Φ (W/m²) from environment flows through the material, the change in temperature is given:

$$\Delta T = \frac{\Phi}{\lambda}$$

where λ is thermal conductivity. In the steady state the linear thermal distortion is determined:

$$\frac{\Delta L}{L_0} = \alpha \cdot \Delta T = \alpha \cdot \frac{\Phi}{\lambda}; \quad \frac{\Delta A}{A_0} = 2\alpha \cdot \Delta T = 2\Phi \cdot \frac{\alpha}{\lambda}; \quad \frac{\Delta V}{V_0} = 3\alpha \cdot \Delta T = 3\Phi \cdot \frac{\alpha}{\lambda};$$

The assumption shows in constant heat flux into the component the distortion (or deflection) due to thermal expansion is proportional to the ratio α/λ . To have good thermal stability, the ratio should be as small as possible.

In the case of transient thermal changes heat storage, the amount of heat Q required to increase the temperature of a unit of a substance by one degree is given by:

$$Q = c_p \cdot m \Delta T$$

where c_p is the heat capacity, and m is the mass of the unit. The diffusivity D is determined by:

$$D = \frac{\lambda}{\rho c_p}$$

For a given amount of heat, in order to keep the temperature change of a certain optical element low, the heat capacity c_p should be as high as possible. To have homogeneous temperature distributions on a component, large diffusivities D are desirable.

Unfortunately the heat capacities of plastic optical materials are extremely low. The plastic component is very sensitive with the heat incident. A large amount of thermal gradient will occur on a component due to small diffusivity; thus the deflection would be large in plastic optical elements. The ratio α/D is proportional to this kind of transient distortion and is expected as small as possible. The selected plastic optical materials with thermal properties are listed in Table 3.

Table 3. Thermal properties and figures of merit of plastic optical materials

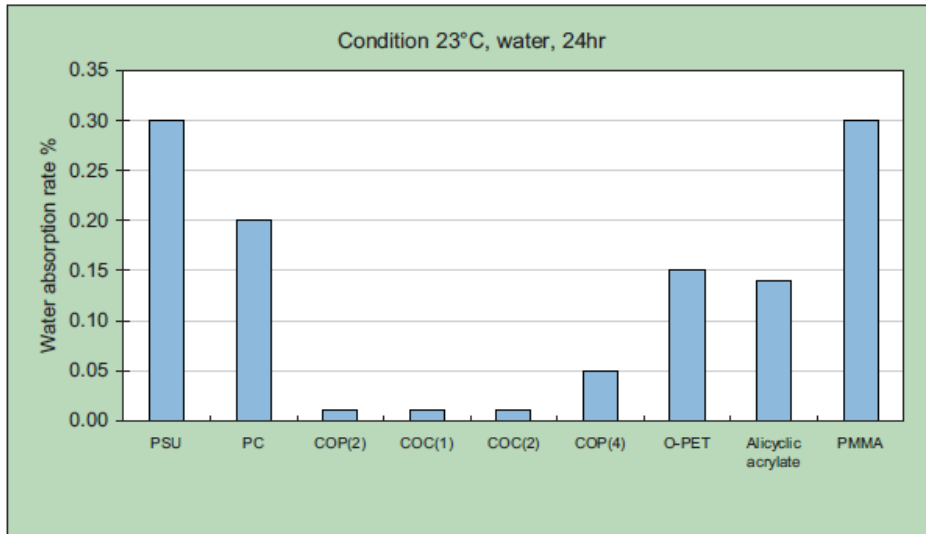
| property | | | max. service temperature, air | refractive index change per degree | coefficient of linear thermal expansion | thermal conductivity | specific heat | thermal diffusivity | steady-state distortion coefficient | transient distortion coefficient |
|--------------------------------|---------|-----------------|-------------------------------|------------------------------------|---|----------------------|---------------------|------------------------|-------------------------------------|------------------------------------|
| symbol | unit | preferred | T_{max} °C | dn/dT $10^{-6}/K$ | α $10^{-6}/K$ | λ W/(m K) | c_p W s/(kg K) | D $10^{-6} m^2/s$ | α/λ mm/W | α/D s/(m ² K) |
| | | | large | small | small | large | large | large | small | small |
| material | abbrev. | trade name | | | | | | | | |
| cyclic olefin copolymer | COC | Topas | 130 | -10.43 | 63 | 0.16 | | | 394 | |
| cycloolefin polymer | COP | Zeonex, Zeonor | 123 | -12.6 | 67 | | | | | |
| polycarbonate | PC | Makrolon, Lexan | 130 | -14.3 | 70 | 0.2 | 1.2 | 0.14 | 348 | 500 |
| poly(methyl methacrylate) | PMMA | Plexiglas | 86 | -8.5 | 72 | 0.21 | 1.4 | 0.13 | 344 | 573 |
| polystyrene | PS | | 80 | -12 | 70 | 0.17 | | | 411 | |
| allyl diglycol carbonate | | CR39 | 100 | | 120 | 0.55 | 1.45 | 0.36 | 218 | 332 |
| poly(styrene-co-acrylonitrile) | SAN | | 77 | | 65 | 0.14 | 1.7 | 0.07 | 464 | 916 |
| poly(styrene-co-methacrylate) | NAS | | 95 | -14 | 65 | | | | | |
| poly(4-methyl-1-pentene) | PMP | TPX | 180 | | 117 | 0.167 | 1.97 | 0.1 | 700 | 1150 |
| amorphous nylon | | Grilamid TR90 | 118 | | 9 | 0.16 | 1.8 | 0.08 | 56 | 108 |
| poly(ether sulfone) | PSU | Udel | 160 | | 56 | 0.26 | | | | |
| poly(ether imide) | PEI | Ultem | 210 | | 55.8 | 0.22 | | | | |
| borCrown glass | | BK7 | | | 7.1 | | 858 | 0.5 | 6.4 | 13.7 |
| aluminum | | AlMg1Si | 580 | | 22.5 | 167 | 896 | 69 | 0.13 | 0.33 |
| Calcium Fluoride | | | | -10.6 | 18.85 | 9.71 | | | 1.94 | |
| Germanium | | | | | 396 | 6.1 | 58.61 | | 0.10 | |
| SF57 | | | | 6.0 | 8.3 | 0.620 | | | 13.39 | |
| Zerodur | | | | 14.3 | 0.05 | 1.46 | | | 0.03 | |

From *Hand Book of Plastic Optics* and Opti 521/421 Prof. Burge Class Note

2.3 Moisture Absorption

Another dimensional instability issue for plastic optical elements is the change of volume in high-humidity environment. Cycloolefin Copolymer (COC) is known as low moisture absorption though PMMA has large moisture absorption needed to be aware (see Fig 3). The coefficient of moisture expansion (CME) for PMMA is about 0.5%.

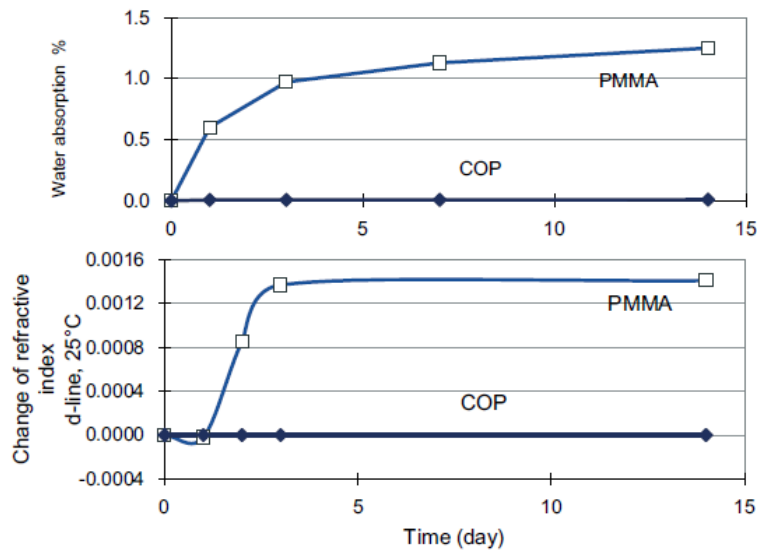
Figure 3. Comparison of the water absorption of selected optical polymers



From Hand Book of Plastic Optics

In figure 4 shows moisture absorption not only results affects on dimensions and densities but also the change of refractive index of plastic optical materials.

Figure 4. Change of refractive index due to water absorption for PMMA

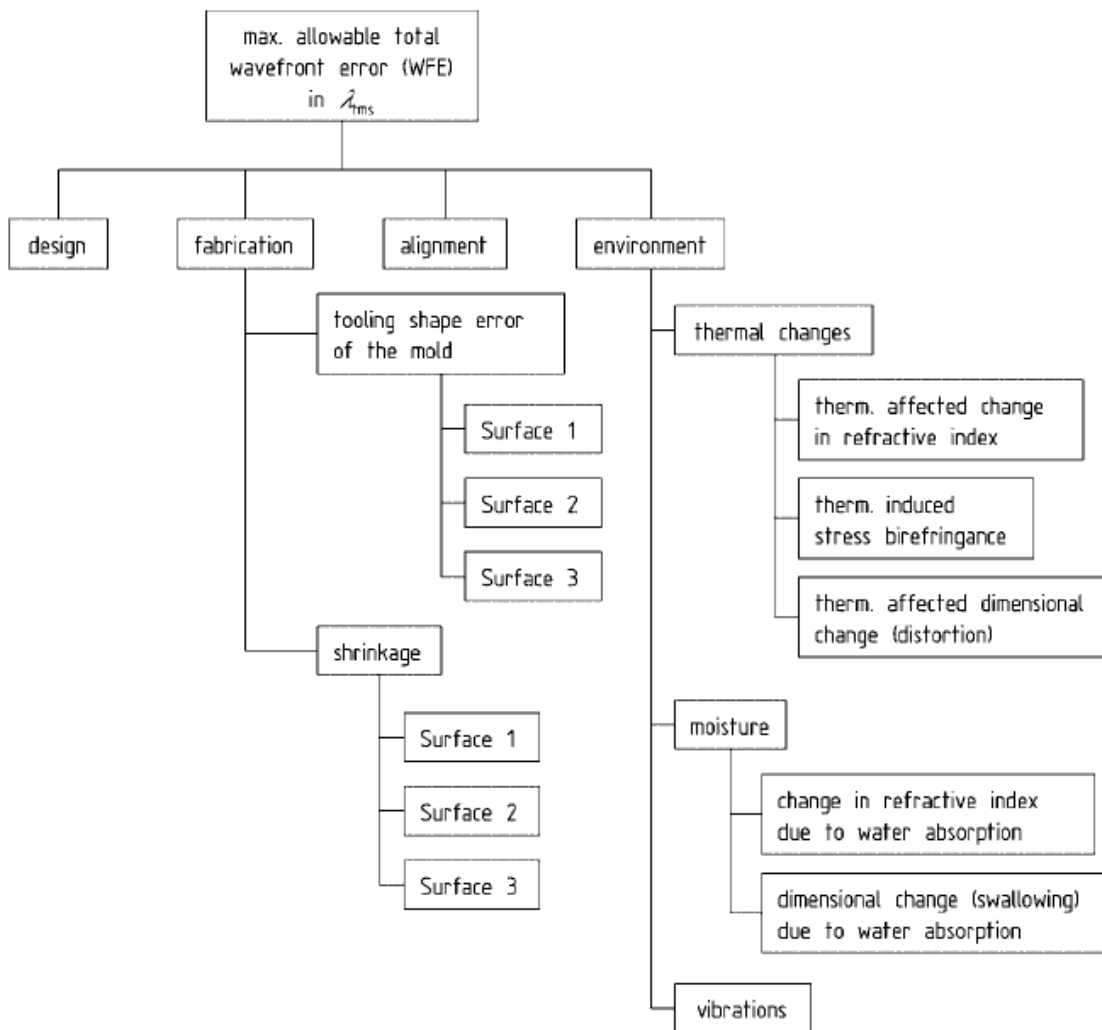


From Hand Book of Plastic Optics

3. Tolerance

Under consideration of determining performance and cost, the deformation possibilities and assembly alignment should be included into the design tolerance. For most of the cases in plastic optics integrating optical and mechanical features, the alignment tolerances are considered inherently into manufacturing tolerances. The main issue of the injection molding methods for creating plastic elements is the shrinkage due to the air existed while the lenses molding. The solution to minimize shape shrinkage can be achieved by adding shrinkage error compensative shape on the modules, which can be estimated by moldflow analysis with thermal model simulation. The other deformation possibility is the environmental susceptibility after fabrication. The material properties are discussed above; besides the change of refractive index due to thermal or humidity environment are needed to be considered as well. A clear wavefront error budget check list is given in Fig 5:

Figure 5. Wavefront error (WFE) budget for the plastic optical component



From *Hand Book of Plastic Optics*

A good table classified four tolerance levels which provided from chapter 2 in *Hand Book of Plastic Optics* is given in Table 4. An additional attention has to be paid on the edge configuration. Due to the stress at the edge especially in injection molding method the effective aperture should be at least 1–2 mm beyond the clear aperture; thus the edge thickness would increase the same amount accompanied by the diameter increasing. The design guideline for injection molding is having at least 1 mm outside the clear aperture and considering corresponding dimension.

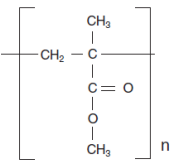
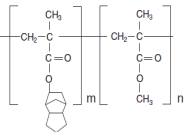
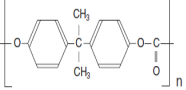
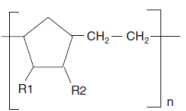
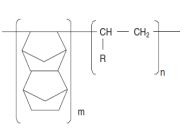
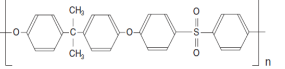
Table 4. Typical tolerances and specification for injection molded plastic optical parts

| | low cost | commercial | state of the art | extremely tight |
|--|----------|------------|------------------|-----------------|
| focal length (%) | ±3–5 | ±2–3 | ±0.5–1 | ±0.5 |
| radius of curvature (%) | ±3–5 | ±2–3 | ±0.8–1.5 | ±0.3 |
| power (fringes) | 10–6 | 5–2 | 1–0.5 | |
| irregularity (fringes/10 mm) | 2.4–4 | 0.8–2.4 | 0.8–1.2 | |
| scratch/dig | 80/50 | 60/40 | 40/20 | |
| centration | ±3' | ±2' | ±1' | |
| center thickness (mm) | ±0.1 | ±0.05 | ±0.01 | ±0.015 |
| flange diameter (mm) | ±0.1 | ±0.05 | ±0.005/∅10 | ±0.015 |
| radial displacement (mm) | 0.1 | 0.05 | 0.02 | |
| repeatability (%) | 1–2 | 0.5–1 | 0.3–0.5 | |
| diameter/thickness ratio | 2:1 | 3:1 | 5:1 | |
| bubbles and inclusions (ISO 10110–3) | | 1 × 0.16 | 1 × 0.10 | 1 × 0.06 |
| surface imperfections (ISO 10110–6) | | 2 × 0.10 | 2 × 0.06 | 2 × 0.04 |
| surface roughness (nm _{RMS}) | 10 | 5 | 2 | |

4. Selected Plastic Optical Materials and Their Characteristics

The challenges with plastic optical materials include the achievement of low birefringence, high refractive index, and high durability (low moisture absorption and high heat resistance). After 90s, new types of polymer are suggested for used. Better durability and lower birefringence improve the performance of plastic optical element. Improved polymers are now under consideration as a result of various recent technology developments. Table 5 is listed the plastic optical materials which most used in current days. More specific coefficients of materials can refer to chapter 5 in *Hand Book of Plastic Optics*.

Table 5. Selected plastic optical material characteristics

| Materials | Type | Chemical Structure | characteristics | Issues | Applications |
|-----------------------------|-------------------|---|--|--|--|
| PMMA | Acrylate Polymers |  | <ul style="list-style-type: none"> . high transparency . low birefringence . outstanding hardness . high light deterioration resistance . high Abbe number | <ul style="list-style-type: none"> . high water absorption . change of refractive index due to absorption . heat resistance | <ul style="list-style-type: none"> . condensers . fresnel lenses . car lamps lenses . light guide plates for LCD backlights |
| Alicyclic Acrylate | Acrylate Polymers |  | <ul style="list-style-type: none"> . low birefringence . low water absorption . high heat resistance | <ul style="list-style-type: none"> . Water absorption is reduced, being approximately half of that of PMMA. | <ul style="list-style-type: none"> . optical lenses . CD pick-up Lenses . LBP lenses |
| Optical Polycarbonate (PC) | Polycarbonate |  | <ul style="list-style-type: none"> . most commonly used . low levels of impurities . transparency . high refractive index . heat resistance . moldability . transferability . high intensity. | <ul style="list-style-type: none"> . large birefringence . the photoelastic coefficient is approximately 10 times greater than that of PMMA. | <ul style="list-style-type: none"> . CD-ROM, CD-R/RW, MD, DVD-ROM, DVD-Video, and DVD-R/RW |
| Cycloolefin Polymer (COP) | Polycarbonate |  | <ul style="list-style-type: none"> . Transparent . The lowest water absorption . Low scattering . Low birefringence . Heat resistance . High processability | | <ul style="list-style-type: none"> . optical devices such as lasers used for the visible region . optical discs . light guide plates for LCD backlights |
| Cycloolefin Copolymer (COC) | Polycarbonate |  | <ul style="list-style-type: none"> . low specific gravity . transparency . low water absorption . low scattering . low birefringence . heat resistance . high processability. | | <ul style="list-style-type: none"> . DVD pick-up lenses . Cell phone camera lenses . Optical lenses |
| Polysulfone (PSU) | |  | <ul style="list-style-type: none"> . Heat resistance. The heat deflection temperature is 343F . High refractive index (>1.6). . High intensity | | <ul style="list-style-type: none"> . food service components . plumbing fixtures . membranes . laboratory animal cages |

From *Hand Book of Plastic Optics*

5. Reference

Stefan Bäumer etc. "*Hand Book of Plastic Optics*", 2005 WILEY

Mike Schaub, "*Practical Plastic Optics*", presentation on plastic optics, Sep 6, 2006

John D. Lytle, "*Specifying glass and plastic optics*", SPIE Vol. 0181, Contemporary Optical System & Components Specification, Apr 1979