Bayfol® HX 200

Description and Application Information

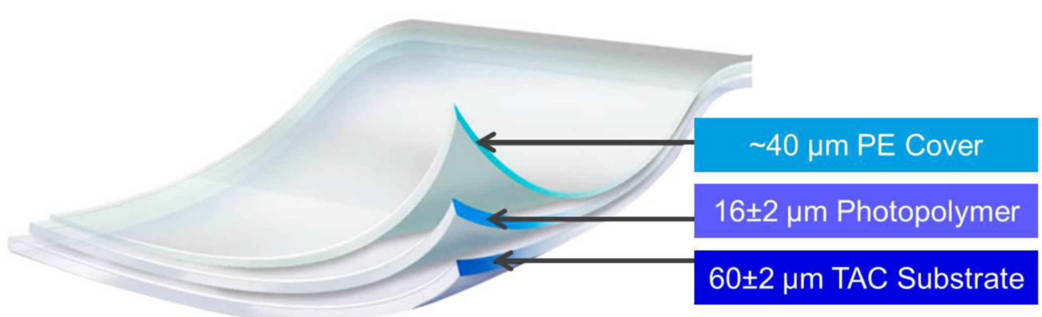
Bayfol® HX 200 is a light-sensitive, self-developing photopolymer film which can be used to produce phase holograms in the form of volume reflection and volume transmission holograms.

Bayfol® HX 200 can be recorded with appropriate laser light within the visible spectral wavelength range from 440 nm to 680 nm. For hologram formation no further post-treatment is necessary, e.g. neither a wet nor a thermal treatment.

Bayfol® HX 200 consists of a three layer stack of a substrate, a light-sensitive photopolymer and a protective cover film. The substrate is a cellulose triacetate film (TAC), and the protective cover is a polyethylene film (PE). The protective cover film can be removed from the photopolymer.

The product is capable of being used for a variety of types of volume holograms.

Layer Stack, Schematic



Bayfol® HX 200

Guideline data [1)]

General properties

Property	Value	Unit of measurement	Method
Typical substrate thickness	60 ± 2	microns	acc. to ISO 4593, 23°C
Typical photopolymer thickness	16 ± 2	microns	white light interferometer
Typical cover layer thickness	40	microns	acc. to ISO 4593, 23°C
Density with cover foil	1.15	g/cm³	ISO 1183, 20°C, Method C

Optical properties

Property	Value	Unit of measurement	Method
Transmittance unrecorded film, w/o cover foil	See spectrum below	%	ASTM E 01348
Haze after UV flood cure[2)]	< 2	%	ASTM D 1003
Index of refraction n_D of the substrate	1.485		Prism coupler
Index of refraction n_D of the photopolymer unrecorded	1.500		Prism coupler
Index of refraction n_D of the photopolymer after UV flood cure [2)]	1.505		Prism coupler

Holographic properties: Denisyuk hologram performance data [3)]

Property	Value	Unit of measurement	Method
Spectral diffraction efficiency η	> 95	%	ISO 17901-1, by transmittance of zero-order transmitted wave
Spectral bandwidth (full width at half maximum)	~ 15	nm	ISO 17901-1, by transmittance of zero-order transmitted wave
Recording dosage (needed to achieve above mentioned values)	~ 30	mJ/cm²	Recording wavelength: λ = 532 nm; Power density: P_R = 4.6 mW/cm²

Bayfol® HX 200

Holographic properties: Reflection hologram performance data [4)]

Property	Value	Unit of measurement	Method
Maximum refractive index modulation Δn_1 per recording wavelength λ			ISO 17901-2
λ = 633 nm	> 0.03		
λ = 532 nm	> 0.03		
λ = 457 nm	> 0.03		
Typical recording dosage needed to achieve above Δn_1 values			ISO 17901-2
λ = 633 nm	~ 15	mJ/cm²	Applied total dosage
λ = 532 nm	~ 20	mJ/cm²	Applied total dosage
λ = 457 nm	~ 25	mJ/cm²	Applied total dosage

Shrinkage and spectral shift

Property	Value	Unit of measurement	Method
Effective thickness shrinkage after recording and UV flood cure [2)]	~ 1.4	%	Reflection holograms
Spectral shift after recording and UV flood cure [2)]	~ -8	nm	Denisyuk holograms: Wavelength deviation between recording and reconstruction

1) All values provide general information and are not part of the product specification.

2) Curing is done by means of a Mercury lamp; Company: Hönle; Typ: MH-Strahler UV-400 H); dosage about 5,000-10,000 mJ/cm².

3) Holographic method: Denisyuk holograms
Reflection holograms are recorded in a Denisyuk setup with an expanded plane-wave laser beam. The backside object is a plane mirror. Schematic figures of the setup are provided in the appendix.

4) Holographic method: Reflection holograms
ISO 17901-2 method to measure the amplitude of refractive index modulation using the reflection hologram, using two expanded plane-wave laser beams. Typical total power density: 9-23 mW/cm². The beams are s-polarized. External angles of incidence are -22° (object beam) and +42° (reference beam) in air, tilted to normal direction. Dosage curves and schematic figures of the setup are provided in the appendix.

Safety	While there are no specific toxic threats, the Bayfol® HX 200 film is a trial product that has not yet been fully tested. As such, safety precautions should be taken during its handling and use. Precautions should be taken to avoid direct contact of the unrecorded photopolymer with skin – gloves or other suitable personal protection devices should be used.
Storage conditions	The unrecorded photopolymer film should be stored in the original and sealed Covestro container that is used for delivery, whenever possible. The storage temperature shall be kept at ≥15°C and ≤ 25 °C. While the recorded film is quite stable, the unrecorded photopolymer film should be protected from light, humidity, heat and foreign materials.
Storage time	The storage time is still under evaluation.
Labelling and REACH applications	**This product data sheet is only valid in conjunction with the latest edition of the corresponding Safety Data Sheet.** Any updating of safety-relevant information – in accordance with statutory requirements – will only be reflected in the Safety Data Sheet, copies of which will be revised and distributed. Information relating to the current classification and labeling, applications and processing methods and further data relevant to safety can be found in the currently valid Safety Data Sheet.

General information about handling instructions under dark room conditions:

The product is light sensitive. Exposure to light prior to the holographic exposure might sacrifice the refractive index modulation Δn_1 and diffraction efficiency η. Examples for tolerable expositions in dark room environment (dim yellow light) without sacrificing the holographic performance are given below:

Property	Value	Unit of measurement	Method
Maximum exposure intensity	2.6 [5)] 0.8 [6)]	µW/cm² µW/cm²	Photopolymer film laminated on glass and illuminant positioned at a distance of 30 cm above
Maximum exposure time	5 [5)] 30 [6)]	min min	See above

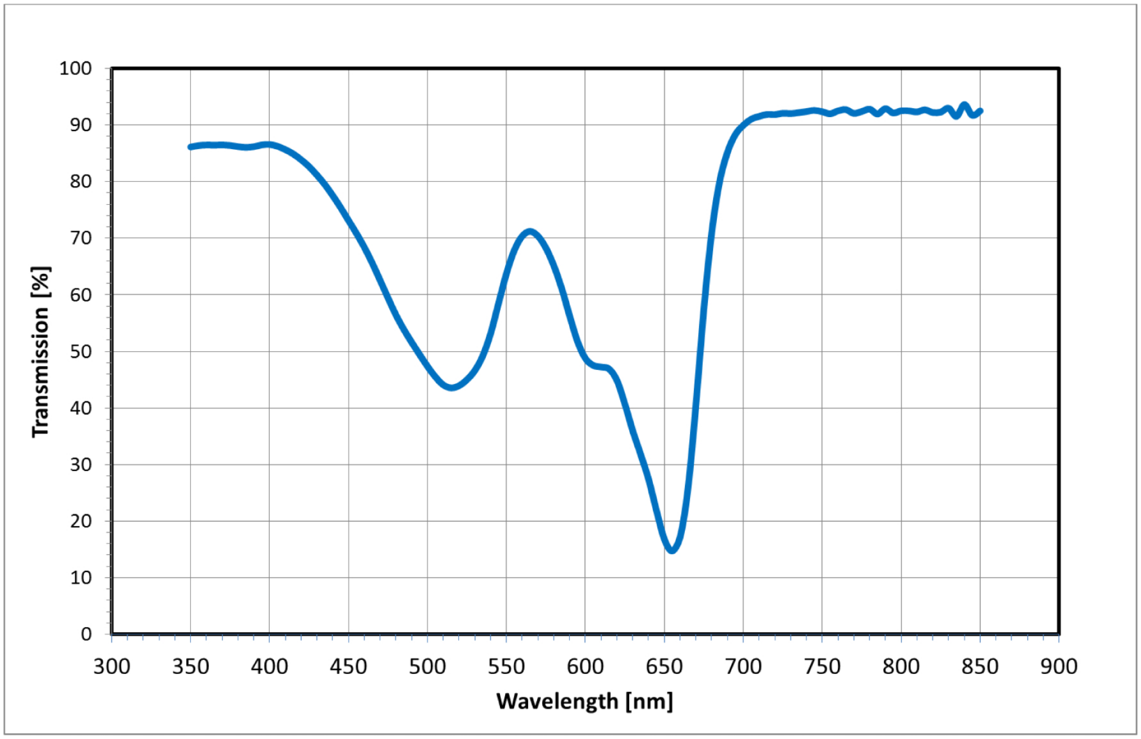
5) Illuminant: OSRAM PARATHOM DECO CLASSIC A Yellow 1 Watt LED E27
6) Illuminant: PHILIPS AccentColor Miniglobe Yellow 1 Watt LED E27

Bayfol® HX 200

Transmission spectrum of the unrecorded photopolymer film:

The transmission spectrum of the unrecorded photopolymer film was recorded after removal of the protective cover film.

The measurement is done in a darkened laboratory with a spectrometer according to ASTM E 01348.



Bayfol® HX 200

General information for flood cure and bleaching:

These are recommendations and should serve as guidelines. According to the specific equipment components and the type of product to be produced, deviations from these guidelines might be necessary. The bleaching can also be adapted to the required product performance.

Example: Conditions for mercury lamps

High temperatures (above 60°C at the film) should be avoided because they can lead to deformation of the substrate. Dichroic mirrors that reflect UV-light and transmit IR-radiation and a fused silica panel in front of the lamp can reduce the amount of IR-radiation and thus further reduce the temperature.

The following conditions were found to be favorable:

- Photopolymer layer on substrate laminated to glass
- Dosage: 5,000-10,000 mJ/cm²
- Intensity at the sample: 40 mW/cm²

These data were found using a mercury lamp (MH-Strahler UV-400 H) of Hönle UV Technology (http://www.hoenle.de).

Determination of the holographic performance:

To determine the holographic performance of Bayfol® HX 200 film, the following samples were prepared: Under dark room conditions first the protective cover film was removed from cut pieces of Bayfol® HX 200 film. Then these pieces were laminated with their photopolymer surface onto glass slides (75 mm x 50 mm x 1 mm) or onto a plane mirror. To facilitate optical contact between the photopolymer layer and the glass surface or mirror surface pressure was applied with a soft roller.

The samples which were prepared as described above were holographically recorded either in a Denisyuk setup, a 2-beam reflection hologram setup in plane-wave geometry.

After the holographic recording and a waiting time of at least 10 seconds the samples were flood cured and bleached with a UV lamp (see above). The performance of the holograms was then determined according to the respective recording geometry with the methods described below.

Denisyuk holograms (plane-wave to plane wave)

In this recording geometry the photopolymer film is laminated onto a plane front surface mirror.

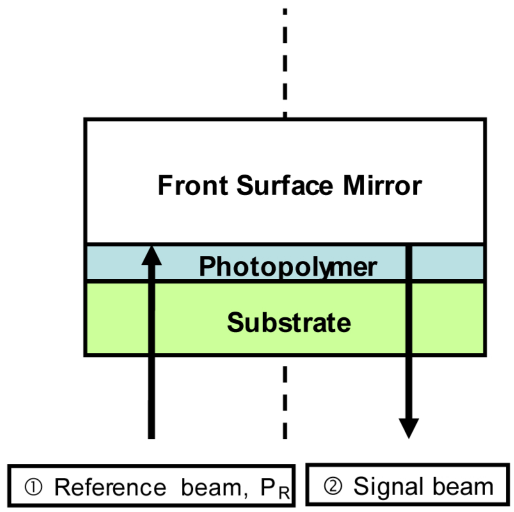
The recording is done with a normal incident collimated laser beam (plane wave). The recording dosage is given by the incident laser power density P_R times the exposure time.

Bayfol® HX 200

Recording of Denisyuk holograms

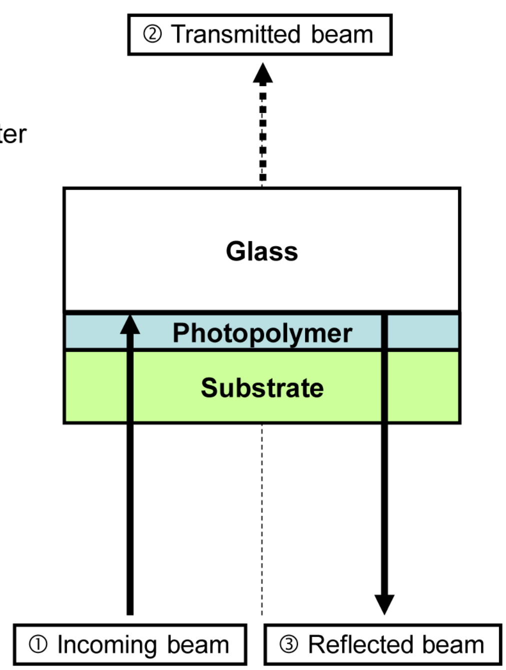
- λ = 532 nm

λ (nm)	P_R (mW/cm²)
532	4.6



Readout of Denisyuk holograms

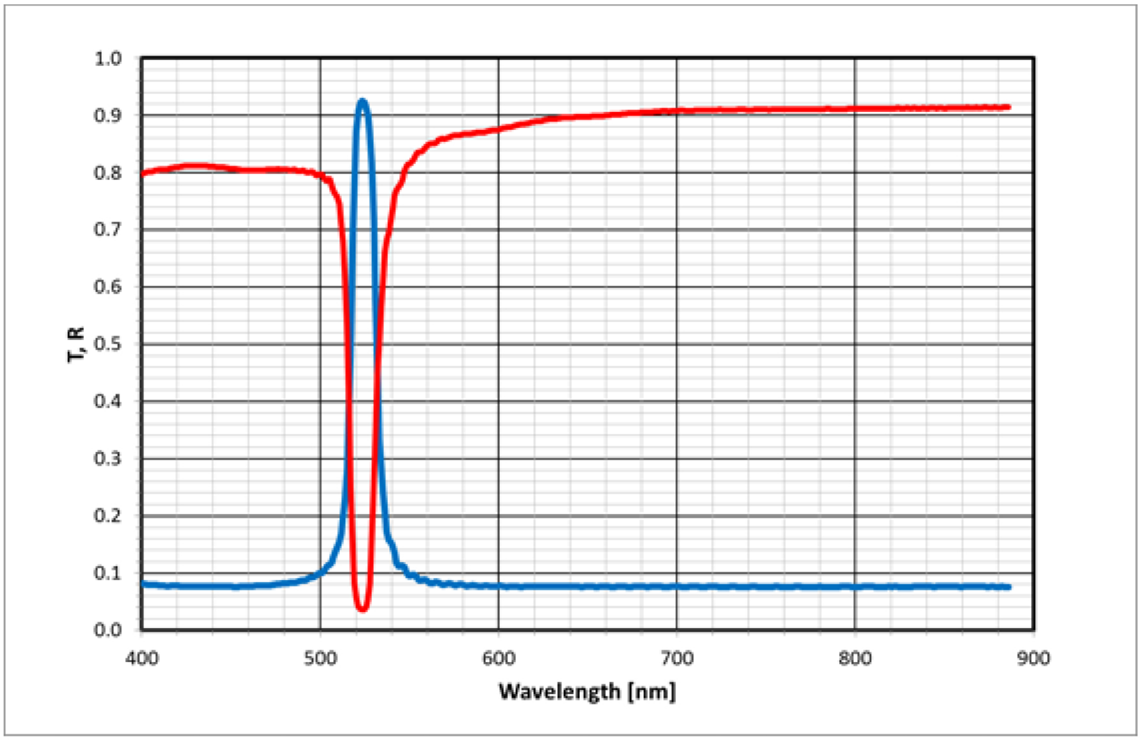
- Transmission and reflection spectrometer
- Evaluation of $\lambda_{reconst.}$ „On Bragg“ cond.
- Evaluation of T_{min} „On Bragg“ ②
- Evaluation of R_{max} „On Bragg“ ③



Bayfol® HX 200

To determine the performance of the hologram, the recorded film sample is re-laminated on a glass plate. Then the transmission spectrum and the reflection spectrum through the hologram at normal incidence are measured with a spectrometer (steag etaoptik, ETA-RT).

From these spectra the above listed performance parameters T_{min}, R_{max}, spectral bandwidth (FWHM) and the spectral shift ($\lambda_{reconst.} - \lambda$) can be extracted. An example of such spectra is shown in the following figure.



Bayfol® HX 200

2-Beam reflection holograms (plane-wave to plane-wave)

In this recording geometry the photopolymer film is laminated onto a glass plate (75 mm x 50 mm x 1 mm).

The holographic recording is done with two coherent and collimated laser beams (plane waves), which penetrate the prepared sample from its two different surfaces. Both laser beams have S-polarization to maximize the interference contrast (fringe visibility) of the holographic recording.

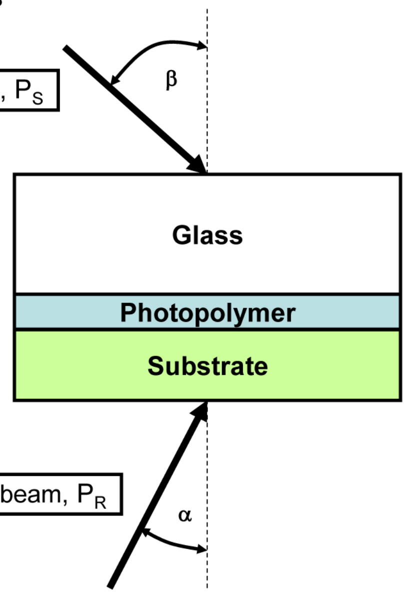
The holographic recording itself is done with dosages which correspond to the product of the total incident power density ($P_R + P_S$) multiplied by the individual exposure times, t. More detailed conditions are depicted in the two following figures.

The ratio (P_S / P_R) = 1.29 compensates for the different size of the projected beam cross sections onto the sample surfaces and the different losses due to Fresnel reflections at the air sample interfaces in such a way that inside the photopolymer layer the beam ratio is equal to 1. This again facilitates maximum fringe visibility during the holographic recording.

Recording of slanted reflection holograms

- λ = 633 nm, 532 nm, 457 nm
- S-Polarization

λ (nm)	α (°)	β (°)	P_R (mW/cm²)	P_S/P_R
633	-22	42	4	1.29
532	-22	42	7	1.29
457	-22	42	10.5	1.29

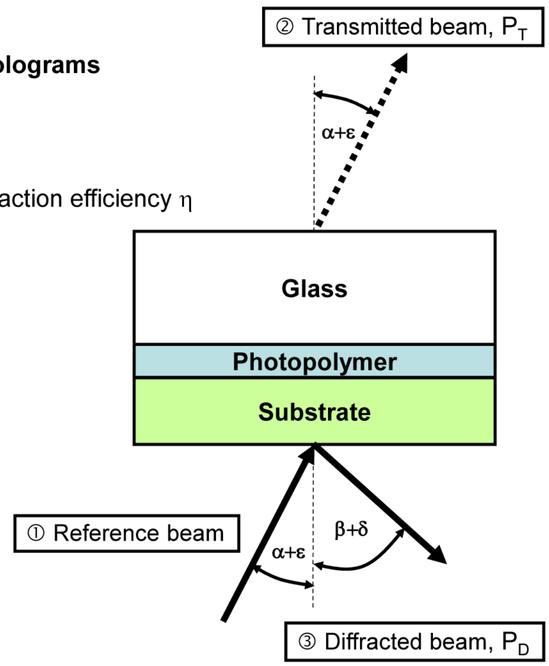


Readout of slanted reflection holograms

- λ = 633 nm, 532 nm, 457 nm
- S-Polarization
- Adjust ε and δ for maximum diffraction efficiency η

$$\eta = \frac{P_D}{P_T + P_D}$$

λ (nm)	α (°)	β (°)
633	-22	42
532	-22	42
457	-22	42

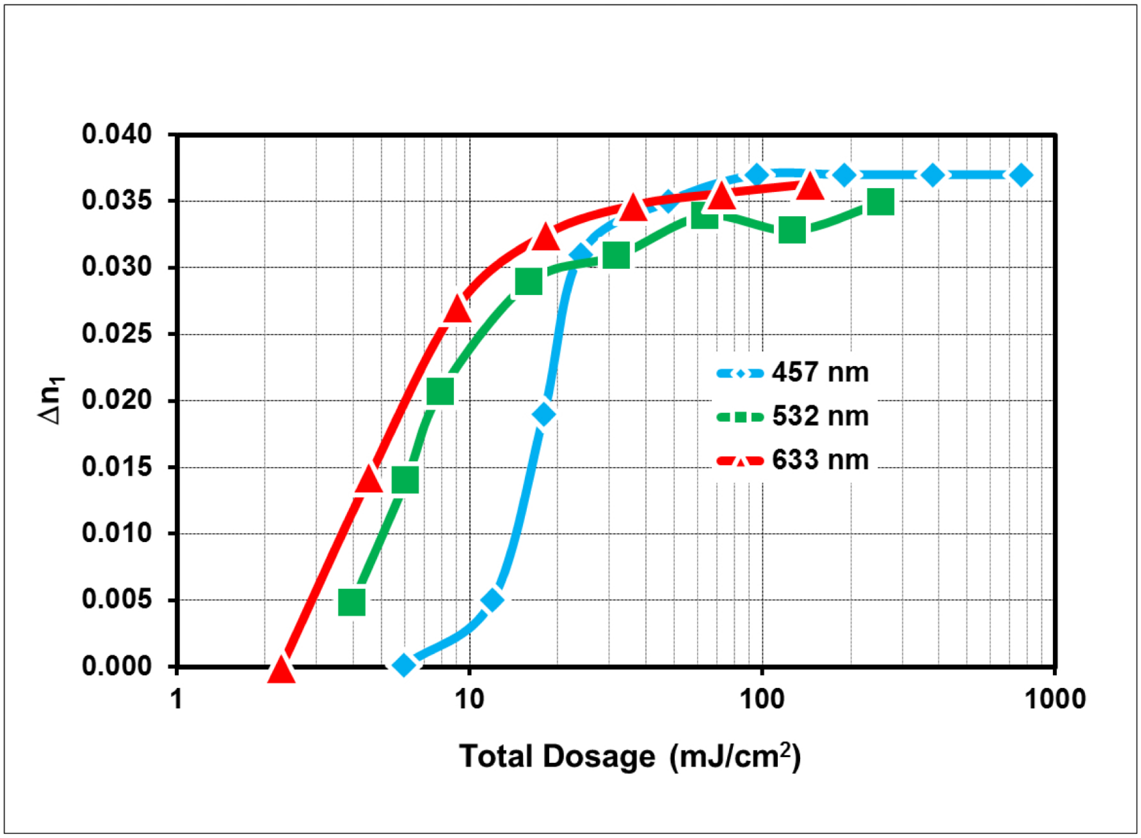


To determine the performance of the hologram, the diffraction efficiency η of the recorded hologram is measured with respect to the rotation angle α (the holographic film / glass sandwich is mounted on a rotation stage). The resulting Bragg curve $\eta(\alpha)$ is analyzed according to the Kogelnik theory*, to deduce the above listed performance parameters η_{max}, Δn_1 and the effective thickness shrinkage. The effective thickness shrinkage is obtained from the angular shift ε, which measures the deviation from the recording angle α to the angle at which η_{max} is achieved. This thickness shrinkage is incorporated in the fit of Δn_1 according to Kogelnik theory.

By varying the recording times the dosage response curves for Δn_1 at the different recording wavelengths, λ = 633 nm, 532 nm and 457 nm, can be obtained.

* Kogelnik, H., "Coupled wave theory for thick hologram gratings", The Bell System Technical Journal 48(9), 2909-2947 (1969)

Bayfol® HX 200



General references to the holographic performance

Bayfol® HX 200 is a light-sensitive, self-processing photopolymer film in which the recording process is based on monomer diffusion caused by the inhomogeneous photopolymerization during holographic exposure. Therefore, the refractive index modulation Δn_1 will in general be dependent on the grating spacing of the recording interference field as generated by the respective holographic recording setup.

Since the grating spacing of transmission holograms is larger than that of reflection holograms, the achievable refractive index modulation Δn_1 is smaller for transmission holograms than for reflection holograms recorded at comparable total power densities. The refractive index modulation Δn_1 for transmission holograms can be increased at a fixed dosage by using lower power densities P_R and P_S at the cost of a longer exposure time t.

Bayfol® HX 200

The photopolymerization in Bayfol® HX 200 film is a free-radical photopolymerization and can be inhibited by oxygen that is, for example, dissolved in the photopolymer layer. Therefore a significant refractive index modulation Δn_1 can be detected only above a specific, minimum dosage. This inhibition dosage is needed to consume all oxygen that was originally dissolved in the photopolymer layer. This inhibition dosage can be overcome also by using a suitable incoherent pre-exposure.

At significantly smaller power densities $P_R + P_S$ and, therefore, much longer illumination times, a reduction of the refractive-index modulation Δn_1 can be observed. This is due to diffusion of oxygen dissolved in the substrate or permeation of oxygen through the substrate into the photopolymer layer during the exposure time period. This additional oxygen further reduces conversion of the free radical photopolymerization which results in smaller Δn_1 values.

In addition the achievable refractive-index modulation Δn_1 can be influenced by the ratio (beam ratio) of the power densities of the signal beam and the reference beam in the above-mentioned recording geometries. The maximum Δn_1 is obtained if this beam ratio is equal to 1 inside the photopolymer layer. The external power density ratio (P_S / P_R) has to be adjusted in such a way that different incident angles and different Fresnel reflection losses at the sample surfaces result in a beam ratio equal to 1 inside the photopolymer layer.

Further Readings

Additional information on Bayfol® HX, its performance data, how to use it and optimize recording and applications in diffractive optics can be found in the following papers and conference proceedings.

- **Integration of volume holographic optical elements (vHOE) made with Bayfol® HX into plastic optical parts**, Proc. SPIE 10944, Practical Holography XXXIII: Displays, Materials, and Applications, 1094402 (1 March 2019); doi: 10.1117/12.2510109.

- **Wavelength multiplexing recording of vHOEs in Bayfol HX photopolymer film**, Proc. SPIE 10676, Digital Optics for Immersive Displays, 106760H (21 May 2018); doi: 10.1117/12.2306956.

- **On the impact of incoherent pre-exposure on vHOE recording in Bayfol HX film for see-through applications**, Proc. SPIE 10558, Practical Holography XXXII: Displays, Materials, and Applications, 105580B (19 February 2018); doi: 10.1117/12.2288495.

- **The Chemistry and Physics of Bayfol® HX Film Holographic Photopolymer**, *Polymers* **2017**, *9*, 472.

- **Thin combiner optics utilizing volume holographic optical elements (vHOEs) using Bayfol HX photopolymer film**, Proc. SPIE 10335, Digital Optical Technologies 2017, 103350D (26 June 2017); doi: 10.1117/12.2270158.

Bayfol® HX 200

- **Mass production of volume holographic optical elements (vHOEs) using Bayfol® HX photopolymer film in a roll-to-roll copy process**, Proc. SPIE 10127, Practical Holography XXXI: Materials and Applications, 101270A (6 April 2017); doi: 10.1117/12.2250933.

- **Performance optimization in mass production of volume holographic optical elements (vHOEs) using Bayfol HX photopolymer film**, Proc. SPIE 10233, Holography: Advances and Modern Trends V, 102330G (15 May 2017); doi: 10.1117/12.2265022.

- **Precision Holographic Optical Elements in Bayfol® HX Photopolymer**, Proc. SPIE 9771, Practical Holography XXX: Materials and Applications, 977103 (March 7, 2016); doi:10.1117/12.2209636

- **Photopolymeric films with highly tunable refractive index modulation for high precision diffractive optics**, Optical Materials Express, Vol. 6, Issue 1, pp. 252-263 (2016)

- **Diffractive optics with high Bragg selectivity: volume holographic optical elements in Bayfol® HX photopolymer film**, Proc. SPIE 9626, Optical Systems Design 2015: Optical Design and Engineering VI, 96260T (23 September 2015); doi: 10.1117/12.2191587

- **A Photopolymer Film Technology Platform for Volume Holographic Optical Elements having a Simplified Recording Process and Tunable Optical Function**, PR15 – Photorefractive Photonics, Villars, Switzerland

- **Diffractive optics in large sizes: computer-generated holograms (CGH) based on Bayfol® HX photopolymer**, Proc. SPIE 9385, Advances in Display Technologies V, 93850C (11 March 2015); doi: 10.1117/12.2077139

- **Edge-lit volume holograms recorded by free-space exposure – diffraction by 2nd harmonics in Bayfol® HX film**, Proc. SPIE 9386, Practical Holography XXIX: Materials and Applications, 938601 (10 March 2015); doi: 10.1117/12.2077868

- **Second harmonics HOE recording in Bayfol® HX**, Proc. SPIE 9508, Holography: Advances and Modern Trends IV, 95080G (May 8, 2015); doi:10.1117/12.2178269

- **Bayfol® HX photopolymer for full-color transmission volume Bragg gratings**, Proceedings of SPIE (2014), 9006(Practical Holography XXVIII), 900602/1-900602/10.

- **Holographic recordings with high beam ratios on improved Bayfol® HX photopolymer**, Proceedings of SPIE (2013), 8776(Holography: Advances and Modern Trends III), 877603/1-877603/12.

Bayfol® HX 200

- **Holographic recording aspects of high-resolution Bayfol® HX photopolymer**, Proceedings of SPIE (2011), 7957(Practical Holography XXV), 79570H/1-79570H/15.
- **Self-Processing, Diffusion-Based Photopolymers for Holographic Applications**, Macromolecular Symposia (2010), 296(Modern Trends in Polymer Science--EPF'09), 133-137.
- **Reaction-diffusion model applied to high resolution Bayfol® HX photopolymer**, Proceedings of SPIE (2010), 7619(Practical Holography XXIV), 76190I/1-76190I/15.
- **Full-color self-processing holographic photopolymers with high sensitivity in red - the first class of instant holographic photopolymers**, Journal of Photopolymer Science and Technology (2009), 22(2), 257-260.
- **New recording materials for the holographic industry**, Proc. of SPIE Vol. 7233, 72330K · © 2009 SPIE · CCC code: 0277-786X/09/$18 · doi: 10.1117/12.809579

Bayfol® HX 200

The manner in which you use and the purpose to which you put and utilize our products, technical assistance and information (whether verbal, written or by way of production evaluations), including any suggested formulations and recommendations, are beyond our control. Therefore, it is imperative that you test our products, technical assistance, information and recommendations to determine to your own satisfaction whether our products, technical assistance and information are suitable for your intended uses and applications. This application-specific analysis must at least include testing to determine suitability from a technical as well as health, safety, and environmental standpoint. Such testing has not necessarily been done by Covestro.
Unless we otherwise agree in writing, all products are sold strictly pursuant to the terms of our standard conditions of sale which are available upon request. All information and technical assistance is given without warranty or guarantee and is subject to change without notice. It is expressly understood and agreed that you assume and hereby expressly release us from all liability, in tort, contract or otherwise, incurred in connection with the use of our products, technical assistance, and information. Any statement or recommendation not contained herein is unauthorized and shall not bind us. Nothing herein shall be construed as a recommendation to use any product in conflict with any claim of any patent relative to any material or its use. No license is implied or in fact granted under the claims of any patent.

This product is not designated for the manufacture of a medical device (1) or of intermediate products for medical devices. This product is also not designated for Food Contact (2), including drinking water, or cosmetic applications. If the intended use of the product is for the manufacture of a medical device or of intermediate products for medical devices, for Food Contact products or cosmetic applications Covestro must be contacted in advance to provide its agreement to sell such product for such purpose. Nonetheless, any determination as to whether a product is appropriate for use in a medical device or intermediate products for medical devices, for Food Contact products or cosmetic applications must be made solely by the purchaser of the product without relying upon any representations by Covestro.

(1) Please see the "Guidance on Use of Covestro Products in a Medical Application" document.
(2) As defined in Commission Regulation (EU) 1935/2004.

This is a trial product. Further information, including amended or supplementary data on hazards associated with its use, may be compiled in the future. For this reason no assurances are given as to type conformity, processability, long-term performance characteristics or other production or application parameters. Therefore, the purchaser/user uses the product entirely at his own risk without having been given any warranty or guarantee and agrees that the supplier shall not be liable for any damage, of whatever nature, arising out of such use. Commercialisation and continued supply of this material are not assured. Its supply may be discontinued at any time.

Editor: CAS Specialty Films
Covestro AG
Kaiser-Wilhelm-Allee 60
D-51373 Leverkusen
www.films.covestro.com
films@covestro.com

Distributed by: Geola Digital Ltd.
Naugarduko 41, LT03227,
Vilnius, Lithuania
www.geola.com
info@geola.com