Manufacture of Contact Lens of Nanoparticle-Doped Polymer Complemented with ZEMAX

Lina M. Shaker 1,*, Ahmed A. Al-Amiery 2,*, Abdul Amir H. Kadhum 3 and Mohd S. Takri 3

1 Laser and Optoelectronics Engineering Department, University of Technology, Baghdad 10001, Iraq
2 Energy and Renewable Energies Technology Center, University of Technology, Baghdad, Baghdad 10001, Iraq; dr.ahmed1975@gmail.com
3 Department of Chemical & Process Engineering, Faculty of Engineering & Built Environment, Universiti Kebangsaan Malaysia, Bangi, Selangor 43600, Malaysia; amir8@ukm.edu.my (A.A.H.K.); sobritakri@ukm.edu.my (M.S.T.)

* Correspondence: linamohammed91@gmail.com; Tel.: +964-771-399-5509

Received: 22 October 2019; Accepted: 17 November 2019; Published: 15 October 2020

Abstract: Many people suffer from myopia or hyperopia due to the refractive errors of the cornea all over the world. The use of high refractive index (RI), Abbe number (νd), and visible light transmittance (T%) polymeric contact lenses (CLs) holds great promise in vision error treatment as an alternative solution to the irreversible laser-assisted in situ keratomileusis (LASIK) surgery. Titanium dioxide nanoparticles (TiO2 NPs) have been suggested as a good candidate to rise the RI and maintain high transparency of a poly(methyl methacrylate) (PMMA)-TiO2 nanocomposite. This work includes a preparation of TiO2 NPs using the sol gel method as well as a synthesis of pure PMMA by free radical polarization and PMMA-TiO2 CLs using a cast molding method of 0.005 and 0.01 w/v concentrations and a study of their effect on the aberrated human eye. ZEMAX optical design software was used for eye modeling based on the Liou and Brennan eye model and then the pure and doped CLs were applied. Ocular performance was evaluated by modulation transfer function (MTF), spot diagram, and image simulation. The used criteria show that the best vision correction was obtained by the CL of higher doping content (p < 0.0001) and that the generated spherical and chromatic aberrations in the eye had been reduced.

Keywords: PMMA-TiO2; contact lens; vision correction; high refractive index; modulation transfer function; image simulation

1. Introduction

It remains a challenging task to evolve a polymer that fulfills all the required features for contact lenses (CLs) applications simultaneously. There has been continual evolution in the CL materials field since these materials were invented. Fundamentally, CLs have been classified into hard, soft, and rigid gas permeable (RGP) according to their elasticity. Even though hard CLs are longer lasting than others, these lenses tend to lose their popularity. Hard CLs are primarily based on hydrophobic materials such as poly(methyl methacrylate) (PMMA), whereas soft CLs are made of biocompatible hydrogels [1].

Recent advances in nanoscience and nanotechnology [2] have facilitated the sciences to develop new polymers hybridized with high refractive index (RI) nanoparticles (NPs). Typically, silicone-hydrogel [3], poly(vinyl alcohol) [4] (PVA) CLs [5], and other plastic polymers [6], in addition to manufacturing techniques, are used to produce transparent (T > 90%), lightweight, and impact-resistant CLs [7]. RGP CLs are expensive and suffer from a lack of hydrophilic monomers, but they are more flexible than PMMA CLs due to their integration with low modulus components and high efficiency in reducing generated aberrations [8].
In general, all soft CLs significantly and adversely affect the tear physiology by reducing tear thinning time and increasing the evaporation rate [9]. All the CL materials discussed above are classified as polymers. To suit optometric applications, the polymer material must be biocompatible, transparent, and able to combine high water content, good mechanical strength, and high refractive index ($n$) and it must have low dispersion ($\nu_d$) to allow optical correction of refractive errors. In this regard, hydrogels have good biocompatibility; however, their mechanical weakness characteristic due to their high water content limits their practical applications [10].

Nevertheless, hydrogel materials with high water content typically have a low $n$ factor and may cause light dispersion. An effective way to increase polymers’ refractive index is by introducing high $n$ inorganic nanoparticles into the organic polymers. Recently, doping with TiO$_2$ [11,12], ZnO [13,14], ZnS [15], ZrO$_2$ [16], Al$_2$O$_3$ [17] NPs, and so on, has been utilized to obtain nanocomposites of high optical quality for nanomaterial applications [18,19]. These nanocomposites can be exploited in CL manufacturing.

The aim of this work was to prepare pure PMMA and PMMA-TiO$_2$ CLs with different TiO$_2$ NP contents. The ZEMAX optical design program is used to evaluate and model the optics of the prepared CLs in comparison with an aberrated human eye. The modulation transfer function (MTF) and image simulation have better assisted us in image analysis.

2. Analysis Criteria

2.1. Modulation Transfer Function

The MTF considers the contrast degradation that occurs in sinusoidal patterns of spatial frequency, or, rather, is the ratio of image contrast to object contrast at all spatial frequencies. Spatial frequency, which measures the capabilities of the human visual system, was examined. The contrast (modulation) of a sinusoidal pattern is defined as [20]

$$MTF = \frac{I_{\text{Max}} - I_{\text{Min}}}{I_{\text{Max}} + I_{\text{Min}}}$$

where $I_{\text{Max}}$ is the irradiance of the peak of the sinusoid and $I_{\text{Min}}$ is the irradiance of the trough of the sinusoid. At a certain value of spatial frequency the MTF will be zero; this spatial frequency value is called the cutoff frequency ($v_{cutoff}$) (measured in cycles/mm in this work) and is given by [21]

$$v_{cutoff} = \frac{1}{\lambda(F/#)}$$

where $F/#$, i.e., $F$/number of an optical system, refers to the ratio of the lens focal length ($F$) to the pupil diameter (PD).

2.2. Root Mean Square (RMS)

A spot diagram is a way of visualizing the aberration effect which is had on image quality and hence lens resolution. RMS refers to the root mean square of the spot in the image plane. It is calculated as the RMS of all distances between each peripheral intersection ($x_i,y_i$) with the image plane and a reference point ($x_0,y_0$) generated by intersection of the chief ray. RMS is computed from Equation (3) [22], i.e.,

$$R_{RMS} = \frac{\sum_{i=1}^{n} (x_i - x_0)^2 + (y_i - y_0)^2}{n}$$
3. Materials and Methods

PMMA polymer was prepared using free radical polymerization (FRP) and TiO$_2$ NPs were prepared using the sol gel method [23]. A solution casting method was used to prepare CLs with different concentrations of TiO$_2$ NPs.

3.1. PMMA Preparation

Materials used for the PMMA polymer preparation were methyl methacrylate monomer (MMA) (C$_5$H$_8$O$_2$), which was obtained from Ruby Dent, tetrahydrofuran (THF) (C$_4$H$_8$O), which was used as a solvent, and benzoyl peroxide (BPO) (C$_{14}$H$_{10}$O$_4$), which was used as an initiator. Ten milligrams of MMA monomer was added to 0.1 g of BPO initiator and THF was added as a solvent. The mixture was then left in a water bath for 24 h at a temperature of 80 °C under nitrogen gas protection. The polymer solution was purified by ethanol twice and left to dry.

3.2. PMMA-TiO$_2$ Preparation

Chloroform was used to dissolve the PMMA polymer. TiO$_2$ NPs (0.1 g) were dissolved in 10 mL of an ethanol and xylene mixture (50:50). Different concentrations of 0.05 and 0.1 mL of the prepared mixture were added to 10 mL of the PMMA polymer to obtain the doped PMMA-TiO$_2$ nanocomposites with 0.005 and 0.01 w/v, respectively.

Scanning electron microscopy was performed by SEM 54032-GE02-0002/8038 (MIRA3/Austria) Austria. Measurement of optical properties of the prepared nanocomposites were carried out by UV-vis transmission spectroscopy using a UV-1601 PC (Shimadzu/Japan) Tokyo 101 Japan. The refractive index was measured using an Abbe refractometer at wavelengths 486.1, 587.6, and 656.3 nm, whereas the Abbe number was calculated using

$$v_d = \frac{(n_d - 1)}{(n_f - n_c)}$$

where $v_d$ is the Abbe number and $n_c$, $n_d$, and $n_f$ are the RI values of the polymer films at wavelengths 656, 589, and 486 nm, respectively.

3.3. Optical Modeling

ZEMAX optical design software was used for modeling the human eye and the manufactured PMMA-TiO$_2$ CLs. The evaluation of these lenses and image simulations were performed at a five-degree field of view (FOV) and at the photopic spectrum (white light) of 470, 510, 555, 610, and 650 nm wavelengths with weights of 0.091, 0.503, 1, 0.503, and 0.107, respectively. The Liou and Brennan eye model (LBEM) [24] was chosen (see Table 1) to evaluate the CLs’ effect. The anterior and posterior corneal surfaces were selected as aspherical surfaces. The pupil diameter was centered nasally by 0.5 mm [25,26] and set at 4 mm.

| Surface               | Radius (mm) | Thickness (mm) | RI   | $v_d$ | Conic | PD (mm) |
|-----------------------|-------------|----------------|------|-------|-------|---------|
| Cornea (anterior cornea) | 7.77        | 0.55           | 1.376| 50.23 | −0.18 | 10      |
| Aqueous (posterior cornea) | 6.40        | 3.16           | 1.336| 50.23 | −0.6  | 10      |
| Pupil                 | Infinity    | 0              | 1.34 | 50.23 | 0     | 4       |
| Lens—front surface   | 12.40       | 1.59           | -    | -     |       | 0       |
| Lens—back surface    | Infinity    | 2.43           | -    | 50.23 | 0.96  | 10      |
| Vitreous humor        | −8.1        | 16.24          | 1.336| 50.23 | 0     | 10      |
| Retina                | −12         | -              | -    | -     | 0     | 10      |
The prepared aspherical CLs were constructed by inserting an extended polynomial surface as the front surface of the applied CL. The front surface radius of the CLs was set at 7.748 mm and its conic at 0.035 while the back surface was set at 7.8 mm and the prepared CL thickness was set at 0.1 mm.

4. Results and Discussion

Pure PMMA CL and 0.005 and 0.01 w/v PMMA-TiO$_2$ CLs were prepared using a cast molding method and are shown in Figure 1. All of the synthesized nanocomposites were transparent, thin, and flexible, and were fabricated with a 0.1 mm thickness and 12 mm diameter.

![Photographs of synthesized samples](image)

**Figure 1.** Photographs of synthesized samples. Legend: PMMA, poly(methyl methacrylate).

4.1. Morphological Properties

Scanning electron monographs of the prepared hybrid PMMA-TiO$_2$ nanocomposites containing 0.05 and 0.1 wt% of TiO$_2$ NPs are shown in Figure 2. From the SEM images, different sizes and shapes of TiO$_2$ NPs can be seen to be imbedded in the PMMA polymer sample. The TiO$_2$ NPs appear as bright points which are well distributed on the PMMA surface; this good distribution helped to improve the behavior of the prepared doped nanocomposites.

![SEM monograph](image)

**Figure 2.** SEM monograph of 0.01 w/v PMMA-TiO$_2$ samples (a) 0.05 and (b) 0.1 wt%.

4.2. UV-Vis Transmission Spectrum

UV-vis transmission spectra of all the nanocomposites are shown in Figure 3 and indicate that the prepared polymer nanocomposites are highly transparent in the visible range. Transmittance of all films is higher than 95%, indicating the homogeneity of hybrid nanocomposites and the compatibility between the PMMA matrix and the inorganic metal. Figure 3 shows that pure PMMA transmits about 98.71% visible light, and due to the effect of doping with TiO$_2$ NPs, this percentage was reduced to 98–96%. However, the prepared nanocomposites were transparent and maintained a value of...
transmittance above 95% in the visible region. The observed higher transmittance for the prepared PMMA-TiO$_2$ nanocomposites is much better than that which has been obtained in some previous investigations [27,28].

![UV-vis transmission spectrum of pure PMMA and 0.005 and 0.01 PMMA-TiO$_2$.](image)

**Figure 3.** UV-vis transmission spectrum of pure PMMA and 0.005 and 0.01 PMMA-TiO$_2$.

4.3. **Refractive Index and Abbe Number**

High refractive index CLs will greatly improve ocular biocompatibility. Figure 4 illustrates the variation of refractive indices with different TiO$_2$ contents. The refractive indices were measured for the prepared hybrid films at 486.1, 587.6, and 656.3 nm wavelengths. The variation of the refractive index with the wavelength components ascribes to the dispersion phenomenon. Each component is refracted by a specific refractive index through the sample. As a result of refractive index variation, the prepared hybrid nanocomposite dispersion values ($n_d$) were calculated from Equation (4) and are listed in Table 2. The index of refraction of the prepared CLs increased with increasing TiO$_2$ NP concentration due to the polymer density increment ($n = c/\rho$), whereas the $n_f$ values exhibit an opposite trend. Such RIs are superior to commercial CLs (1.43) as well as those which have been reported by others [29,30]. Doping with NPs of a higher refractive index than the pure PMMA refractive index increases the refractive index of the nanocomposites. For high optical quality, the particle size must be as small as possible to avoid the scattering effect.

![Variation of refractive index with TiO$_2$ content at specific wavelengths.](image)

**Figure 4.** Variation of refractive index with TiO$_2$ content at specific wavelengths.
Table 2. Refractive index and Abbe number of the prepared samples.

| PMMA-TiO₂ (w/v) | 486.1 nm | 587.6 nm | 656.3 nm | νd  |
|-----------------|----------|----------|----------|-----|
| 0               | 1.497    | 1.491    | 1.488    | 53.32 |
| 0.005           | 1.507    | 1.497    | 1.496    | 45.61 |
| 0.01            | 1.615    | 1.602    | 1.596    | 31.00 |

4.4. Polychromatic MTF

The retinal image sharpness (spatial frequency value) and contrast (MTF value) are characterized by MTF criteria. For optimal retinal image quality, the lens should perform over 50% (0.5) contrast at 20 cycles/mm. The maximum spatial frequency was set at 30 cycles/mm as the optimum contrast area. Five-degree off-axis polychromatic MTF simulations were obtained for the simulated CLs compared to the free eye. A polychromatic MTF simulation is presented in Figure 5 which clearly shows that all of the hybrid CLs exhibited high image contrast at low frequencies (less than 20 cycles/mm), while the contrast value was degraded over 20 cycles/mm. The best vision correction was realized when 0.01 PMMA-TiO₂ CL was used; for PMMA-TiO₂ CL the area under the MTF curve was as large as possible. The other CLs made of pure PMMA and 0.005 PMMA-TiO₂ exhibited almost similar behavior; vision was not corrected when they were applied but worsened. This is evidence that the image performance had been affected by refractive index variation. Although the doping process was done with the addition of small amounts of TiO₂ NPs, it appeared to have a clear impact on the refractive index and thus on prepared hybrid CL efficiency.

![Figure 5](image-url)  
**Figure 5.** Polychromatic modulation transfer function (MTF) simulation curves of prepared contact lenses (CLs) in compare with a free eye.

Pure organic PMMA CL with RI = 1.491 and νd = 53.32 achieved the worst MTF indication at 50%. On the contrary, the best contrast was obtained when the polymer was doped with 0.1 mL of TiO₂ NPs, for which the MTF value was improved above 50% due to its optimum refraction properties and high transmissivity in visible light. There was a significant difference between pure PMMA and the doped PMMA. Where the difference in the contrast and sharpness was noteworthy was at the 50% and 20 cycles/mm intersection point. White light significantly degraded the visual quality of all cases. This degradation can be attributed to the presence of chromatic aberration in addition to the monochromatic aberrations in the eye, i.e., spherical, coma, astigmatism, and distortion aberrations [31]. Chromatic aberration results from the separation of white light into its wavelength components and
the focusing of these components on different focal points [32]. These aberrations were reduced when the high TiO$_2$ content CL was inserted on the eye.

4.5. Spot Diagram

Spot diagrams of an LBEM eye of RMS = 3.295 and treated eyes with different CL concentrations are presented in Figure 6. When pure PMMA and 0.005 PMMA-TiO$_2$ CLs were inserted, the highest spot sizes were obtained and RMS was 7.518 and 4.206 µm, respectively. These CLs enlarged the spot sizes and increased their RMS by more than the LBEM eye because chromatic aberrations further reduced the image quality in addition to monochromatic aberrations (spherical, coma, and astigmatism aberrations). The image deformation was treated by 0.01 PMMA-TiO$_2$ CL, spot size was minimized, RMS = 2.738 µm, and a high image performance was obtained.

(a) 

(b)

Figure 6. Cont.
Figure 6. Comparison of the formed retinal image (a) without CL, (b) with PMMA CL, (c) with 0.005 PMMA-TiO$_2$ CL, and (d) with 0.01 PMMA-TiO$_2$ CL.

4.6. Image Simulation

A formed image of each model is shown in Figure 7. 0.01 PMMA-TiO$_2$ CL revealed the best image clarity with polychromatic light sources. The images formed by the prepared lenses without NP addition (PMMA-only) and using 0.005 PMMA-TiO$_2$ CLs were blurred and worse than the retinal image formed by the eye without CL. The generated spherical, coma, and astigmatism aberrations prevented the formed image from being sharp where the rays from the object point did not focus into a single focal point. There was no noticeable improvement in image contrast and this proved what has been discussed in the MTF analysis. Only the highest refractive index CL carried out the best image correction.
The authors gratefully acknowledge the University of Technology/Iraq for providing the facilities for this work.

Funding: This research was funded by UKM-USD, grant number 020-2017 “Malaysia.”

Acknowledgments: The authors gratefully acknowledge the University of Technology/Iraq for providing the facilities for this work.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Goda, T.; Ishihara, K. Soft contact lens biomaterials from bioinspired phospholipid polymers. Expert Rev. Med. Devices 2006, 3, 167–174. [CrossRef] [PubMed]
2. Gaaz, T.S.; Sulong, A.B.; Kadhum, A.A.H.; Ba-Abbad, M.; Al-Amiery, A.A. Enhancement of physical and chemical properties of halloysite nanotubes using sulfuric acid. Wulfenia 2015, 22, 264–284.
3. Tummala, G.K.; Rojas, R.; Mihranyan, A. Poly(vinyl alcohol) Hydrogels Reinforced with Nanocellulose for Ophthalmic Applications: General Characteristics and Optical Properties. J. Phys. Chem. B 2016, 120, 13094–13101. [CrossRef] [PubMed]
4. Gaaz, T.S.; Al-Amiery, A.A.; Hussein, E.K. Physical Properties of Halloysite Nanotubes-Polyvinyl Alcohol Nanocomposites using Malonic Acid Crosslinked. J. Kejuruter. 2017, 29, 71–77. [CrossRef]
5. Kita, M.; Ogebra, Y.; Honda, Y.; Hyon, S.-H.; Cha, W.-I.; Ikada, Y. Evaluation of polyvinyl alcohol hydrogel as a soft contact lens material. Graefes Arch. Clin. Exp. Ophthalmol. 1990, 228, 533–537. [CrossRef] [PubMed]
6. Maldonado-Codina, C.; Efron, N. Dynamic wettabiltiy of pHEMA-based hydrogel contact lenses. Ophthalmic Physiol. Opt. 2006, 26, 408–418. [CrossRef] [PubMed]
7. Seo, E.; Kumar, S.; Lee, J.; Jang, J.; Park, J.H.; Chang, M.C.; Kwon, I.; Lee, J.-S.; Huh, Y.-I. Modified hydrogels based on poly(2-hydroxyethyl methacrylate) (pHEMA) with higher surface wettability and mechanical properties. Macromol. Res. 2017, 25, 704–711. [CrossRef]
8. Shokrollahzadeh, F.; Hashemi, H.; Jafarzadehpur, E.; Mirzajani, A. Corneal aberration changes after rigid gas permeable contact lens wear. J. Curr. Ophthalmol. 2016, 20, 1–5.
9. Thai, L.C.; Tomlinson, A.; Doane, M.G. Effect of Contact Lens Materials on Tear Physiology. Am. Acad. Optom. 2004, 81, 194–204. [CrossRef] [PubMed]
10. Gaaz, T.S.; Sulong, A.B.; Kadhum, A.A.H.; Al-Amiery, A.A.; Nassir, M.H.; Jaaz, A.H. The Impact of Halloysite on the Thermo-Mechanical Properties of Polymer Composites. Molecules 2017, 22, 838. [CrossRef]
11. Benhabiles, O.; Galiano, F.; Marino, T.; Mahmoudi, H.; Lounici, H.; Figoli, A. Preparation and Characterization of TiO2-PVDF/PMMA Blend Membranes Using an Alternative Non-Toxic Solvent for UF/MF and Photocatalytic Application. Molecules 2019, 24, 724. [CrossRef] [PubMed]
12. Sathish, S.; Shekar, B.C.; Bhavyasree, B.T. Nano composite PVA–TiO2 thin films for OTFTs. Adv. Mater. Res. 2013, 678, 335–342. [CrossRef]
13. Demir, M.M.; Koyonov, K.; Bubeck, C.; Park, I.; Lieberwirth, I.; Wegner, G. Optical Properties of Composites of PMMA and Surface-Modified Zincite Nanoparticles. Macromolecules 2007, 40, 1089–1100. [CrossRef]
14. Ba-Abbad, M.M.; Kadhum, A.A.H.; Al-Amiery, A.A.; Mohamad, A.B.; Takriff, M.S. Toxicity evaluation for low concentration of chlorophenols under solar radiation using zinc oxide (ZnO) nanoparticles. Int. J. Phys. Sci. 2012, 7, 48–52.
15. Xu, J.; Zhang, Y.; Zhu, W.; Cui, Y. Synthesis of Polymeric Nanocomposite Hydrogels Containing the Pendant ZnS Nanoparticles: Approach to Higher Refractive Index Optical Polymeric Nanocomposites. Macromolecules 2018, 51, 2672–2681. [CrossRef]
16. Xia, Y.; Zhang, C.; Wang, J.X.; Wang, D.; Zeng, X.F.; Chen, J.F. Synthesis of Transparent Aqueous ZrO2 Nanodispersion with a Controllable Crystalline Phase without Modification for a High-Refractive-Index Nanocomposite Film. Langmuir 2018, 34, 6806–6813. [CrossRef]
17. Cai, B.; Kaino, T.; Sugihara, O. Sulfonyl-containing polymer and its alumina nanocomposite with high Abbe number and high refractive index. Opt. Mater. Express 2015, 5, 1210. [CrossRef]
18. Jassim, H.A.; Khadhim, A.; Al-Amiery, A.A. Photo catalytic degradation of methylene blue by using CuO nanoparticles. Int. J. Comput. Appl. Sci. 2016, 1, 1–4. [CrossRef]
19. Wasmi, B.; Al-Amiery, A.A.; Kadhum, A.A.H.; Takriff, M.S.; Mohamad, A.B. Synthesis of vanadium pentoxide nanoparticles as catalysts for the ozonation of palm oil. Ozone Sci. Eng. 2016, 38, 36–41. [CrossRef]
20. Hecht, E. Geometrical Optics. In Optics, 5th ed.; Pearson Education Limited: London, UK, 2017; p. 216.
21. Schaub, M.; Schwiegerling, J.; Fest, E.C.A.; Shepard, R.H. Molded Optics: Design and Manufacture; Taylor and Francis Group LLC: Boca Raton, FL, USA, 2011; pp. 128–129.
22. Geary, J.M. Introduction to Lens Design with Zemax; Scientific Research; Willmann-Bell Inc.: Richmond, VA, USA, 2002.
23. Kamil, F.; Hubiter, K.A.; Abed, T.K.; Al-Amiery, A.A. Synthesis of Aluminum and Titanium Oxides Nanoparticles via Sol-Gel Method: Optimization for the Minimum Size. J. Nanosci. Technol. 2016, 2, 37–39.
24. Liu, H.L.; Brennan, N.A. Anatomically accurate, finite model eye for optical modeling. J. Opt. Soc. Am. A Opt. Image Sci. Vis. 1997, 14, 1684–1695. [CrossRef] [PubMed]
25. Westheimer, G. Image Quality in the Human Eye. Opt. Acta Int. J. Opt. 1970, 17, 37–41. [CrossRef] [PubMed]
27. Sugumaran, S.; Bellan, C.S. Transparent nano composite PVA-TiO$_2$ and PMMA-TiO$_2$ thin films: Optical and dielectric properties. *Optik* 2014, 125, 5128–5133. [CrossRef]

28. Jin, J.; Qi, R.; Su, Y.; Tong, M.; Zhu, J. Preparation of high-refractive-index PMMA/TiO$_2$ nanocomposites by one-step in situ solvothermal method. *Iran. Polym. J.* 2013, 22, 767–774. [CrossRef]

29. Yuwono, A.H.; Xue, J.; Wang, J.; Elim, I.; Ji, W. Transparent nanohybrids of nanocrystalline TiO$_2$ in PMMA with unique nonlinear optical behavior. *J. Mater. Chem.* 2003, 13, 1475–1479. [CrossRef]

30. Tao, P.; Viswanath, A.; Li, Y.; Rungta, A.; Benicewicz, B.C.; Siegel, R.W.; Schadler, L.S. Refractive Index Engineering of Polymer Nanocomposites Prepared by End-grafted Polymer Chains onto Inorganic Nanoparticles. *Mater. Res. Soc.* 2011, 1359, 163–168. [CrossRef]

31. Castejo’n-Mocho’n, J.; Lo’pez-Gil, N.; Benito, A.; Artal, P. Ocular wave-front aberration statistics in a normal young population. *Vis. Res.* 2002, 42, 1611–1617. [CrossRef]

32. Thibos, L.N.; Bradley, A.; Zhang, X. Effect of ocular chromatic aberration on monocular visual performance. *Optom. Vis. Sci.* 1991, 68, 599–607. [CrossRef]

**Publisher’s Note:** MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.