Passive athermalisation of compact imaging lens and camera using TLens® tunable lens.

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1 Abstract

poLight ASA is the owner of and has developed the TLens® products family as well as other patented micro-opto-electro-mechanical systems (MOEMS) technologies. TLens® is a focusable tunable optics device based on lead zirconium titanate (PZT) microelectromechanical systems (MEMS) technology and a novel optical polymer material. The advantages of the TLens® have already been demonstrated in multiple products launched on the market since 2020. Compactness, low power consumption, and fast speed are clear differentiators in comparison with incumbent voice coil motor (VCM) technology, thanks to the patented MEMS architecture. In addition, the use of TLens® in the simple manner by adding it onto a fixed focus lens camera, or inserting the TLens® inside the lens stack, enables stable focusing over an extended operating range. It has been demonstrated that the TLens® passively compensates the thermal defocus of the plastic lens stack/camera structure. The fixed focus plastic lens stack cameras, usually used in consumer devices, typically exhibits a thermal defocus of a few diopters over the operating temperature range.
Results of simulations as well as experimental data are presented together with a principal athermal lens design using TLens® in only a passive manner (without the use of its electro-tunablity) while the electro-tunability can be used to additionally secure an extended depth of focus with further enhanced image quality.

Keywords: athermalisation, camera, lens design, focus, tunable lens, TLens®

1 Introduction

The TLens® is an electrically tunable lens that can change focus by an applied voltage. It is made of an optical soft polymer sandwiched between two optical surfaces, one flexible glass membrane and one rigid, called the back window [1, 2]. The glass membrane is a part of the piezoelectric micro-electro-mechanical systems (MEMS) actuator and is attached to a silicon frame. The piezoelectric layer, other stack of layers, electrodes, passivation and an anti-reflective coating (ARC) are deposited on top of the glass membrane. The actuator is deposited around the optical aperture of the TLens®, which needs to remain transparent to the wavelength range of interest for the application. Today, poLight TLens® products have been optimized mainly for the visible spectrum to support cameras for mobile phone, consumer, medical, industrial, and wearable applications. It is also possible to tune its performance to other wavelength ranges, like near-infrared applications. More detailed description of the poLight TLens® can be found in [3].

The piezoelectric film deposited onto the glass membrane acts as a bimorph actuator. By applying a voltage to the electrodes of the piezoelectric layer, it contracts and bends the glass membrane to a spherical shape and deforms the polymer to create the variable focusing lens (Figure 1).

The Figure 2 gives a cross section view of the TLens® product implementation.

The piezoelectric actuator in poLight TLens® is a thin film PZT sandwiched between a bottom electrode and a top electrode.

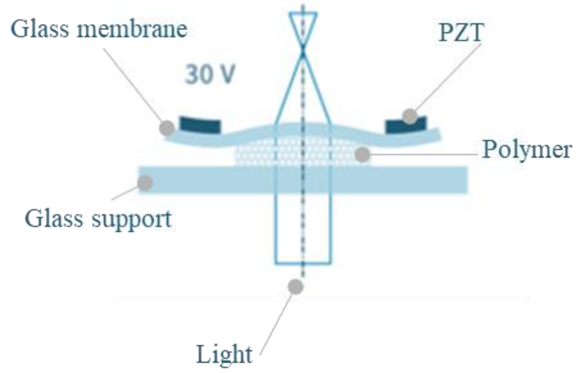

Figure 1 TLens® concept.

Figure 3 is a picture of the first poLight product, “TLens® Silver”, which has been implemented in the cameras and imaging devices of several commercially available end OEM products.

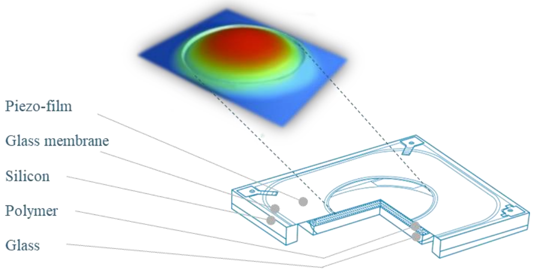

Figure 2 poLight TLens® implementation.

PZT is the predominant piezoelectric material used in actuators and sensors.

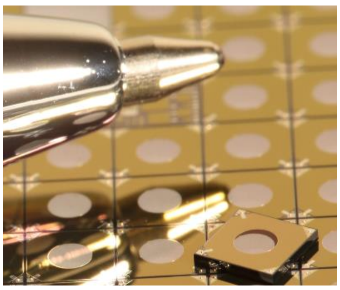

Figure 3 Picture of TLens® Silver.

2 TLens® basic performances

poLight has established a method to characterise the focusing performance of the tunable lens (tunable optical power) as well its optical performance in terms of unwanted aberrations or wavefront error (WFE) which affects the image quality, often referred to as the modulation transfer function (MTF) [6].

The optical performance of the TLens® has been optimised to be close to the diffraction limit, since the root mean square wavefront error (RMS WFE) of the light transmitted/refracted by the TLens® is in the range of 20 to 50 nm over the entire range of focusing. Figure 4 represents a measurement data of the optical power variation through the voltage range given in diopters on the left axis while the RMS WFE is given on the right axis.

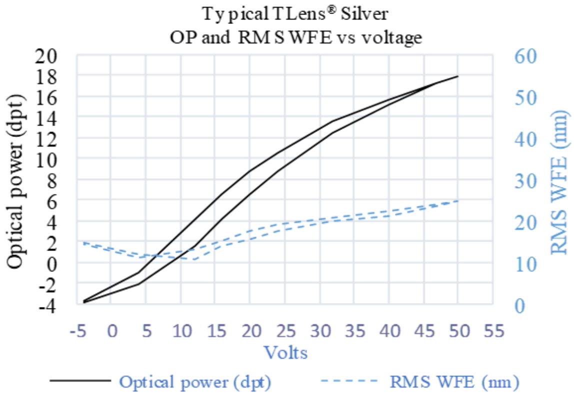

Figure 4 Typical performance of a TLens® Silver

From the optical power curve, we can observe that due to the hysteresis from the PZT actuator, the curves of optical power on the upward voltage direction or downward voltage direction are slightly different. Methods to compensate for the hysteresis effects have been developed by poLight.

3 TLens® performance over temperature

The measurements of TLens® test system are acquired by a SLSYS wavefront analyser (wavefront sensor developed specifically for poLight by Imagine-Optic, Orsay, France) including a controlled thermal chamber to enable temperature controlled measurement of the TLens®

The test setup is schematically represented in Figure 5, as well as the picture of the thermal chamber given in Figure 6.

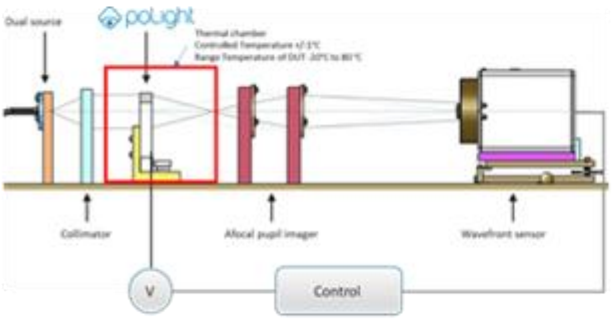

Figure 5 Schematic setup of SLSYS wavefront analyser workbench

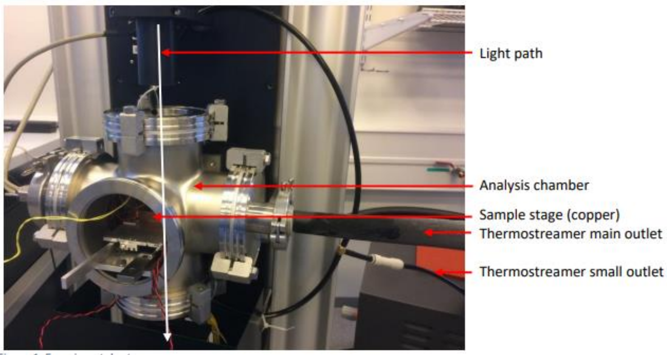

Figure 6 Picture of SLSYS wavefront and Thermal Chamber

The detailed FEM COMSOL simulation of TLens® has been developed to predict the focusing, optical performance, thermal behaviour, as well as TLens® integration method in the optical devices. The model is based on known material properties and detailed structure of the MEMS as well as empirical data provided by dedicated design of experiments and confidential know-how. The model has proven to be accurate, predictable, and aligned with real test performances of the TLens® [3].

FEM simulation of the TLens® predicted a shift of about +1.8 diopters for a temperature changing from room conditions of +20°C up to 80°C, which is in line with the experimental results.

Figure 7 provides a typical TLens® behaviour over temperature. poLight can provide a mathematical expression of the typical TLens® behaviour for further simulation at the system level. However, this cannot be easily implemented in a simple Zemax model of the TLens® by using existing available models based on thermal coefficient of expansion and index of refraction of the material used.

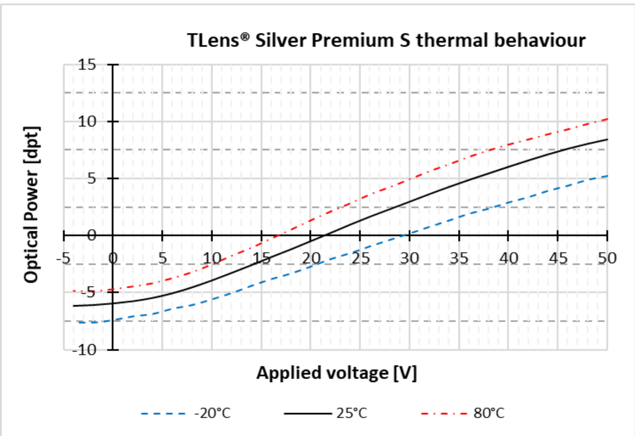

Figure 7 Experimental data of the TLens® behaviour over -20°C to 80°C temperature range.

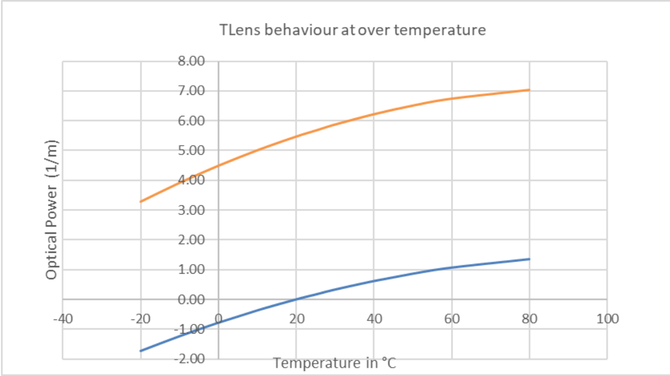

Figure 8 TLens® Optical power variation over temperature for 2 optical power levels

It is interesting to note that the thermal behaviour of the TLens® is the opposite to most of the lenses based on plastic elements. Indeed, when the temperature of a plastic lens (with positive optical power, convergent lens) increases, the index of refraction reduces, while the dimension expands and the optical power of such lens decreases. Correspondingly, with a temperature decrease, the opposite effect happens.

Therefore, TLens® in combination with a plastic lens system will be more stable over a given temperature range. In the next section, we will describe the phenomena based on a more detailed model of an entire camera module as well as provide experimental data that proves the thermal stability of a TLens® camera module.

4 Camera with no TLens®

Cameras for mobile and consumer market mainly use plastic lenses and plastic barrels and mounts to assemble and focus the lens in front of the image sensor. Plastic material has higher coefficient of linear expansion than glass and metal. Consequently, the index variation of the optical plastic material over temperature is known to be at least 10 times higher than for that of the glass material.

Due to the above reason, automotive cameras typically do not use plastic lenses and plastic mechanical structures, since the operating temperature range is much wider than for consumer cameras. Indeed, automotive operating temperature range must cover -40°C to 105°C (AEC-Q100 Grade 2) while consumer temperature requirement is more in the range of -20°C to 80°C or less.

Athermal design of plastic refractive lens is extremely challenging if not impossible, especially when considering the constraints of compactness and the high optical quality requirements which have to be met for the demanding consumer applications.

For most of the lens designs for mobile or consumer cameras, the first lens element of the lens stack and the plastic mount used to hold the lens on top of the image sensor are usually the biggest contributors to thermal defocus. At least, this can be considered valid for a wide range of lenses, that are called the front aperture lenses.

The simplified model for estimation of the thermal defocus of a lens stack can be represented by Figure 9. The camera can be represented by a single plastic lens of equivalent effective focal length (EFL) of the lens stack, a lens mount, and an image sensor.

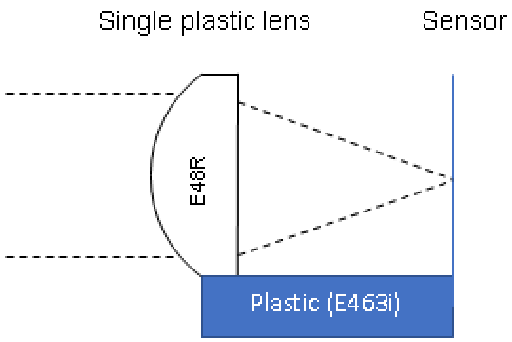

Figure 9 Simplified illustration of a plastic mobile or consumer camera

The following formula can be deduced from the geometrical optics formula, so the optical power variation over the temperature is then given by equation 1:

$$dOP(\Delta T) = \frac{1}{EFL}\left(TCN \; - TCE_L\right)\Delta T + \frac{BFL}{EFL^2} TCE_M \,\Delta T$$

Equation 1 Relation between optical power defocus and equivalent defocus in µm

Where;

a) EFL is the effective focal length
b) BFL is the back focal length (distance from the last lens element to the image sensor)
c) TCN is the index relative thermal variation coefficient
d) TCE_L is the thermal Coefficient of Expansion for lens
e) TCE_M the thermal Coefficient of Expansion for mount

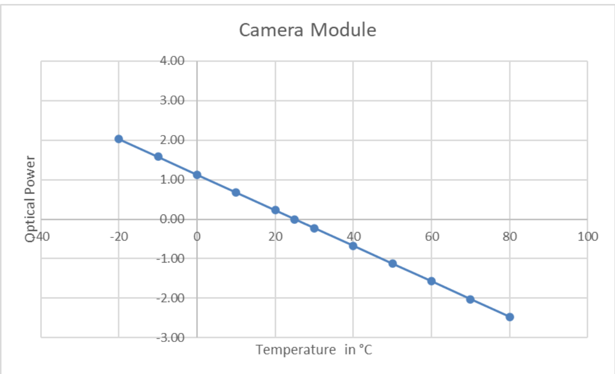

Figure 10 Camera optical power variation over temperature

The graph shown in Figure 10 has been obtained by simulating a slightly more complex structure using the thermal Zemax simulation of a real lens stack combined with the TLens® added on top as well as the mechanical structure of the camera module, which is depicted in Figure 11 and described in [5].

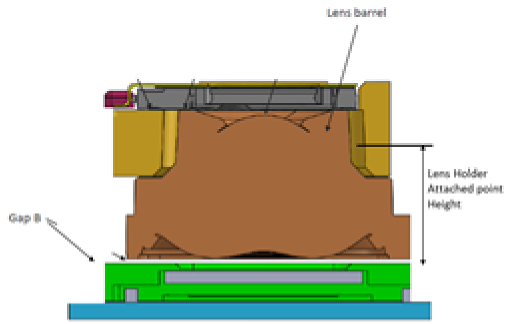

Figure 11 Cross-section of a camera module

The simulation has taken into account the glue under the image sensor as well as the glue between the lens mount and the sensor, together with the IR filter plastic frame for a more precise estimation of the thermal defocus of the camera module.

The TCN of the plastic lens has been modeled as -2.13E-04 (corresponding to the Zeonex E48R) and the other mechanical properties of the different components are summarized in the table here below:

Lens Holder Attached Point Height	GapB Glue	Green Part	Glue under Green part	Glue sensor	**Name of Mechanical part**
2	0.15	0.91	0.07	0.05	**Thickness(mm)**
4.25E-05	6.00E-05	4.25E-05	6.00E-05	1.80E-05	**Coef of exp mm/°C**

Table 1 Properties of different materials used in a camera module per Figure 11

5 Athermal TLens® camera

The thermal defocus of a plastic lens camera module can be calculated by using the following formula in Equation 2:

$$Defocus(\Delta T) = EFL\left(TCN \; - TCE_L\right)\Delta T + BFL\; TCE_M \,\Delta T$$

Equation 2 Simplified thermal defocus

We can also use the first order approximation between the optical power and the equivalent defocus in micrometers in the sensor space to express the overall temperature of a camera module using a TLens® per Equation 3:

$$\text{Defocus(OP)} = \text{EFL}^2 * \text{OP}$$

Equation 3 Relation between optical power defocus and equivalent defocus in µm.

Where the defocus is expressed in micrometer and the EFL is given in mm with OP expressed in diopter (1/m).

By combining the TLens® mounted on top of a fixed focus camera module we can create a more stable solution over a wider operating temperature range. Indeed, the thermal defocus can be reduced without special design change from 3.5 diopters of defocus between -20 to 60°C for the plastic lens camera module standalone to less than 0.5 diopter defocus by simply combining a TLens® with the same camera module (Figure 12).

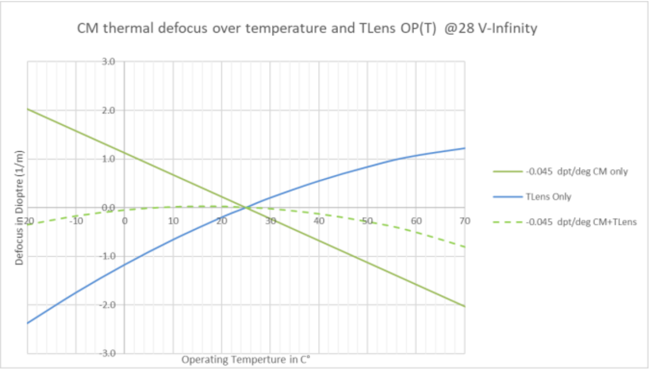

Figure 12 Athermalisation effects of TLens® when combined with plastic lens camera module

It is important to note that this result is obtained even without using the tunability of the TLens® but only using it passively. Obviously, the tunability of the TLens® can be leveraged in addition to enhance the depth of focus of the camera.

6 Athermal TLens® camera test results

poLight has verified that indeed the theoretical athermalisation occurs in real cameras by testing a mass production TLens® camera module, that incorporate a plastic lens stack, shipping in a system OEM product.

The test was performed on a camera module that uses a 1/3'' 13-megapixels image sensor with a f-number of 2 and a full diagonal field of view of 80°. The cameras tested are like the one used in the simulation in section 5.

The camera and the resolution target altogether with the illumination source were placed in an oven to characterize the camera module over temperature range from 20°C to 60°C which is illustrated on Figure 13.

Figure 13 Picture of the oven used with TLens® camera module test setup

Ten (10) TLens® camera modules have been tested between these temperatures and the resolution target has been used to measure the through focus curve. The shift of the through focus curve is indicating the defocus between temperatures as plotted in Figure 14. All TLens® camera modules have shown similar behaviors.

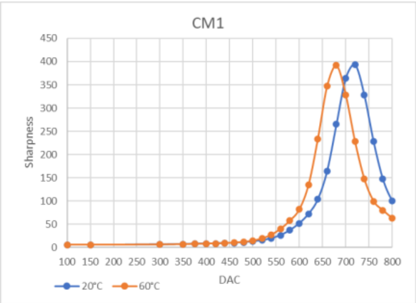

Figure 14 Typical through focus curve at different temperatures

Table 1 below summarizes the test results and translates the residual DAC differences in terms of optical power variations of the camera modules. The characteristic of the poLight driver ASIC (PD50), DAC(V) and the TLens® optical power OP(V) have been used to estimate the residual defocus over the temperature range in diopters.

CM	Max Sharp. (20°C)	Max Sharp, (60°C)	DAC (25cm/20°C)	DAC (25cm/60°C)	ΔDAC (60-20°C)	dOP (60-20°C)	Equ. Defoc (um) (60-20°C)
CM1	394	392	716	678	-38	-0.56	-7.02
CM2	410	403	752	710	-42	-0.62	-7.83
CM3	311	311	631	614	-17	-0.25	-3.10
CM4	353	349	655	637	-17	-0.26	-3.22
CM5	290	328	691	657	-33	-0.49	-6.15
CM6	302	287	648	609	-39	-0.57	-7.19
CM7	311	350	774	738	-36	-0.53	-6.68
CM8	260	240	664	618	-46	-0.67	-8.50
CM9	314	297	656	618	-38	-0.55	-6.94
CM10	318	327	672	638	-35	-0.51	-6.40
				Average	**-34**	**-0.5**	**-6.3**
				Std.dev	*10*	*0.1*	*1.8*

Table 2 Summary table of TLens® camera module thermal defocus

The results are in line with expectations. It is also interesting to note that the image quality remains good since the maximum sharpness score is very similar at both temperatures of 20°C and 60°C.

7 Principal athermal lens design with TLens®

This paper is mainly addressing the combination of a TLens® with a fixed focus camera module in an "add-on" structure. It is important that the same principle and behaviour have been demonstrated for an "add-in" structured TLens® camera module, where the TLens® is added into the lens stack. Moreover, it is also possible by lens design optimisation to secure the athermalisation benefits even further.

The following paragraphs give an example of a fully athermalised design in a TLens® camera module with a 160° field of view, 2.3 f-number lens, with TLens® added inside the lens stack.

This particular design employs a hybrid lens that consists of both glass spherical and plastic aspherical elements. Mixed usage of plastic and glass lenses allows for securing much higher optical and image quality parameters compared to a pure glass lens, while enabling the system to stay compact.

Figure 15 demonstrates a principal layout of such a design. This could potentially be optimized to be athermalised with no TLens®, but that would reduce the degree of freedom to optimize the overall performances of the lens stack. Therefore, adding a TLens® inside the stack can make sense to athermalise any given lens system.

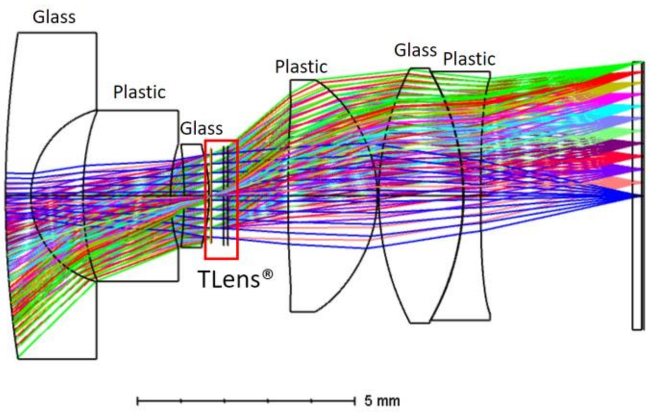

Figure 15 Principal layout of an athermalised lens design using the TLens® added in

The main disadvantage is, as described earlier, plastic material's high thermal expansion index together with high dependency of a refraction index over temperature.

Figure 16 represents MTF versus field of view plots for 20°C, –20°C and 80°C temperatures without TLens® passive compensation.

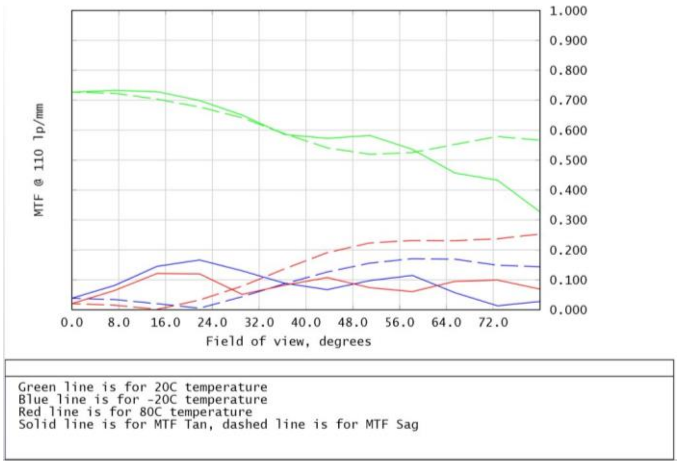

Figure 16 MTF versus field of view for different temperatures without TLens® passive compensation

Evidently, the blue and red curves, representing -20°C and 80°C, respectively, show very low MTF levels for both sagittal (dashed) and tangential (solid) due to thermal defocus.

On the contrary, Figure 17 shows that by just inserting a TLens® inside the lens element stack the thermal defocus becomes negligeable.

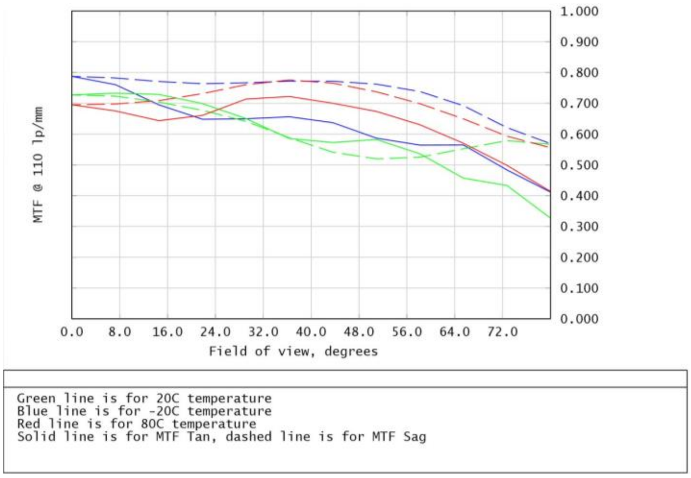

Figure 17 MTF versus field of view for different temperatures with TLens® add-in passive compensation

The blue and red curves, representing -20°C and 80 °C, respectively, show MTF levels for both sagittal (dashed) and tangential (solid) sections comparable with the green curve, representing 20°C.

Thus, without any additional TLens® focusing or voltage applied, by having it simply assembled inside the optical lens stack, it is possible to achieve good MTF performance for a wide temperature range.

8 Conclusion

Based on TLens® properties, experimental data and optical design results presented in this paper, it is demonstrated that the use of TLens®, added onto a fixed focus lens camera module or added into the lens stack of a camera module, enables stable focusing over an extended operating temperature range in a passive manner and compensates the plastic lens stack/camera's structural thermal defocus.

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