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f/1.6 diffraction-limited air-spaced Cooke triplet photographic lens designs for MWIR and LWIR imaging applications: geometrical optics performance comparison between Ge–ZnSe–Ge and Si–Ge–Si triplet designs using Zemax

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ABSTRACT

In this study Ge–ZnSe–Ge (spectral range 8–14 μm) and Si–Ge–Si (spectral range 3–11 μm) air-spaced photographic objective triplet lens designs are discussed. The two designs have focal length of 90 mm, f/1.6 and full field-of-view (FOV) of ± 4.5°. Geometrical optics calculations obtained with Zemax® for each lens design are provided for the modulation transfer function (MTF), point spread function (PSF), encircled energy, transverse ray fan plots, root-mean-square wave front error (RMS WFE), chromatic focal shift, field curvature, distortion, and RMS WFE versus wavelength. Furthermore, the MTF at 50% contrast modulation for both designs is evaluated over the temperature range 20–40 °C. The results indicate that the Ge–ZnSe–Ge triplet design is more susceptible to temperature variations, which lead to loss in image quality with the rise in ambient temperature

1. Introduction

The Cooked triplet photographic objective lens was designed by H. Dennis Taylor in 1893. The triplet lens consists of a negative lens placed between two positive lenses. And it was the first photographic lens that allowed the reduction of the first and third order aberrations (i.e., spherical, coma, astigmatism, field of curvature, distortion, axial chromatic, and lateral chromatic) to a value close to zero using the triplet lens 14 degrees of freedom (i.e., six radii of curvatures, three types of glass, three lens thicknesses, and two interelement airspaces) [1–3].

Infrared imaging in the midwave (MWIR, spectral range 3–5 μm) and longwave (LWIR, spectral range 8–12 μm) has wide range of industrial and military applications, such as glass and metal processing, surveillance, building and construction, packaging, leak detection and inspection [4–10].

In this work, optical performance metrics comparing f/1.6 (focal length = 90 mm, field-of-view (FOV) ± 4.5°) diffraction-limited Ge–ZnSe–Ge (spectral range 8–14 μm) and Si–Ge–Si (spectral range 3–11 μm) air-spaced photographic triplet lens designs are given. Fast Fourier transform modulation transfer function (FFT MTF), point spread function (PSF), encircled energy, transverse ray fan plots, root-mean-square wave front error (RMS WFE), chromatic focal shift, field curvature, distortion, and RMS WFE versus wavelength calculations obtained with Zemax® [11,12] are discussed. Finally, the MTF at 50% contrast modulation for the two lens designs is evaluated over the temperature range 20–40 °C.

2. Lens files for the optimized air-spaced Ge–ZnSe–Ge and Si–Ge–Si triplet designs

Key lens parameters and the operation spectral band for the Ge–ZnSe–Ge and Si–Ge–Si air-spaced triplet lens designs are tabulated in Table 1. Fig. 1 is a 2-D layout for the Ge–ZnSe–Ge triplet lens. The lens prescription for the Ge–ZnSe–Ge triplet lens shown in Fig. 1 is given in Table 2. The 2-D layout for the Si–Ge–Si triplet lens is similar to the design shown in Fig. 1 and the lens prescription for the Si–Ge–Si lens is given in Table 3.

Optimization for the two photographic lens files was performed by setting the lens curvatures, thicknesses, and the air spacing to independent variables. Furthermore, optimization of each lens design was performed by selecting the centroid of the RMS spot radius and the Gaussian curvature options in the optimization merit function. Additionally, axial symmetry was assumed in the merit function setting. The starting designs for both lenses were based on the Ge–ZnSe–Ge, and the Si–Ge–Si air-spaced triplet designs described in Laikin's book (chapter 3: The Air-Spaced Triplet) [1].

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Table 1
Key parameters for the Ge–ZnSe–Ge and Si–Ge–Si air-spaced photographic triplet lens designs.

	Ge–ZnSe–Ge	Si–Ge–Si
Wavelength range	8–14 μm	3–11 μm
Focal length	89.08 mm	90.04 mm
Total track	114.85 mm	162.18 mm
Total mass	138.87 g	164.79 g
F/#	1.60	1.64
FOV	+/−4.5°	+/−4.5°

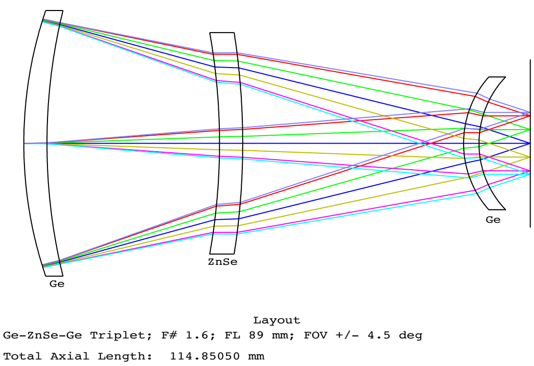

Fig. 1. 2-D layout showing the Ge–ZnSe–Ge air-spaced triplet photographic lens design (f/1.6, focal length = 89 mm and FOV = ± 4.5°).

Table 2
Lens prescription for the Ge–ZnSe–Ge air-spaced triplet photographic lens design shown in Fig. 1.

Radius (mm)	Thickness (mm)	Glass	Lens Diameter (mm)
93.172	5.258	Ge	60.00
125.691	39.120	Air	
−141.517	5.258	ZnSe	50.00
−162.243	50.085	Air	
22.557	3.491	Ge	30.00
21.657	11.640	Air	

Table 3
Lens prescription for the Si–Ge–Si air-spaced triplet photographic lens design.

Radius (mm)	Thickness (mm)	Glass	Lens diameter (mm)
104.493	15.000	Si	40.00
308.761	6.655	Air	
511.860	16.000	Ge	40.00
166.420	76.840	Air	
28.231	8.000	Si	24.00
27.646	5.287	Air	

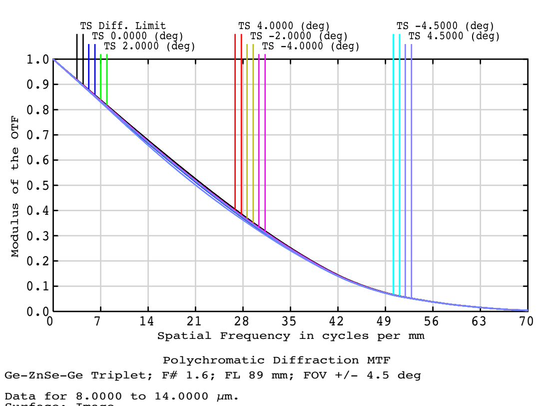

Fig. 2. FFT MTF plot (modulation or contrast vs. spatial frequency) for the Ge–ZnSe–Ge air-spaced triplet lens. At 50% modulation the lens spatial frequency is 20.0 cycles/mm.

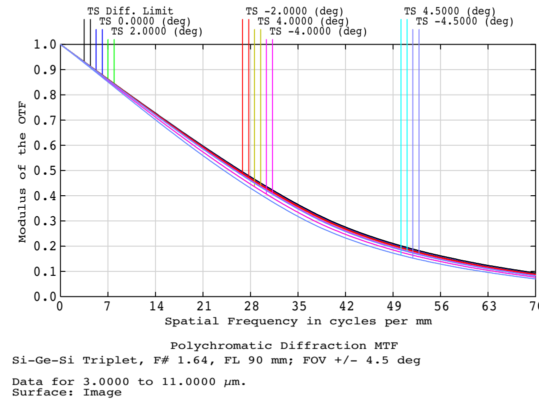

Fig. 3. FFT MTF plot for the Si–Ge–Si air-spaced triplet lens. At 50% modulation the lens spatial frequency is 26.5 cycles/mm.

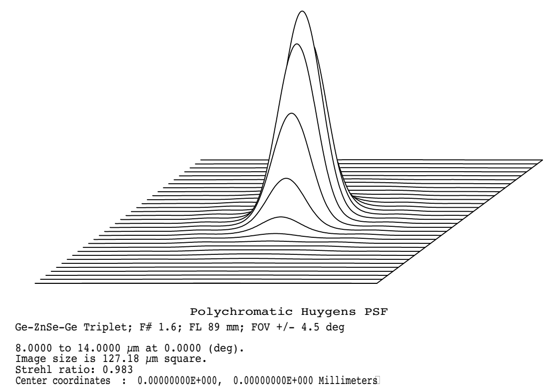

Fig. 4. Plot showing the calculated Huygens PSF for the Ge–ZnSe–Ge triplet lens design. The calculated Strehl ratio = 0.983.

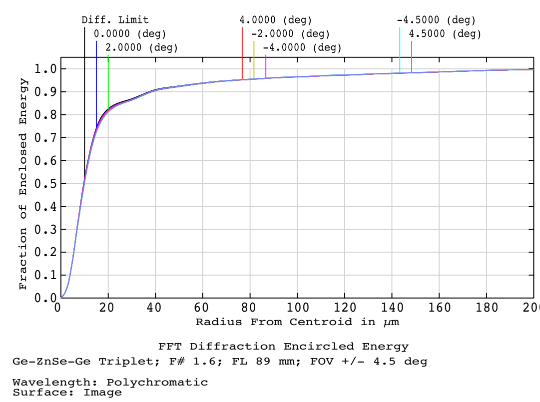

Fig. 5. Calculated encircled energy plot for the Ge–ZnSe–Ge triplet lens design showing diffraction limited performance. At 80% fraction of enclosed energy 18 μm focused spot radius from the centroid is achieved.

3. Results and discussion

The MTF curves for the Ge–ZnSe–Ge and Si–Ge–Si triplets are plotted individually in Figs. 2 and 3. The MTF for the Si–Ge–Si triplet design shows a higher contrast modulation (or contrast) than that of the Ge–ZnSe–Si triplet lens and higher ability to resolve spatial frequencies beyond 70 cycles/mm (or lp/mm). Further, as shown in Figs. 2 and 3 both MTF plots demonstrate the diffraction-limited performance. At 50% contrast modulation the Ge–ZSe–Ge and the Si–Ge–Si triplets can achieve 20.0 cycles/mm and 26.5 cycles/mm, respectively.

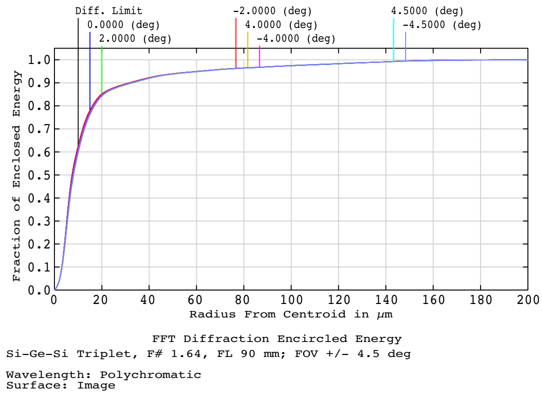

Fig. 6. Calculated encircled energy plot for the Si–Ge–Si triplet lens showing diffraction limited performance. At 80% fraction of enclosed energy 16 µm focused spot radius from the centroid is achieved.

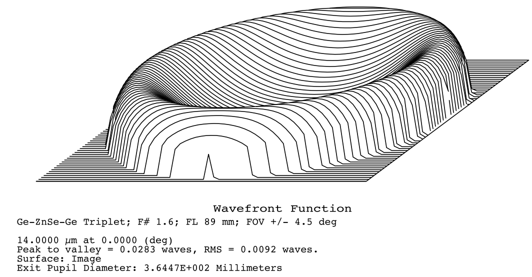

Fig. 9. Calculated wave front error (WFE) plot for the Ge–ZnZe–Ge triplet lens at the image plane. The RMS WFE = 0.0092 waves for the Ge–ZnZe–Ge triplet design and RMS WFE = 0.0035 waves for the Si–Ge–Si triplet lens design.

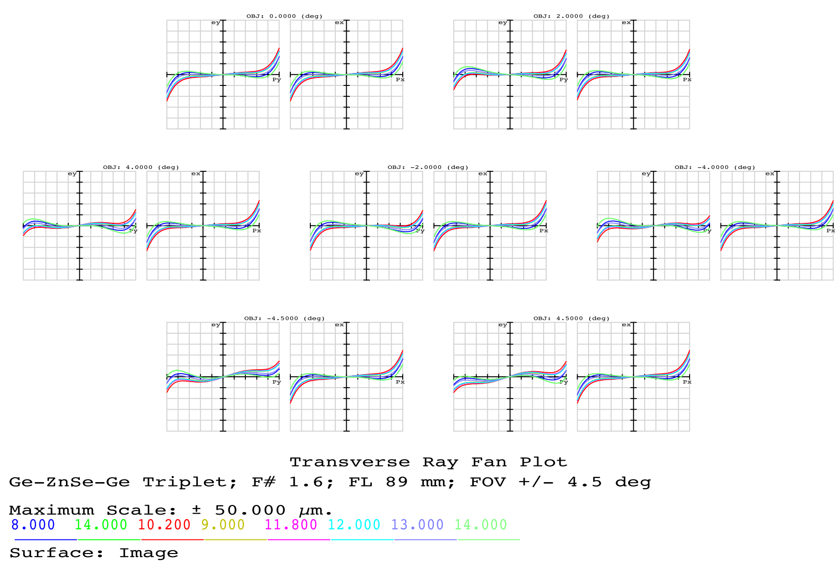

Fig. 7. Transverse ray fan plots for the Ge–ZnZe–Ge triplet lens over the full FOV. The maximum plot scale is ± 50 µm. The aberration plots are calculated in the image plane and represent the transverse ray aberration as a function of the pupil x and y coordinates.

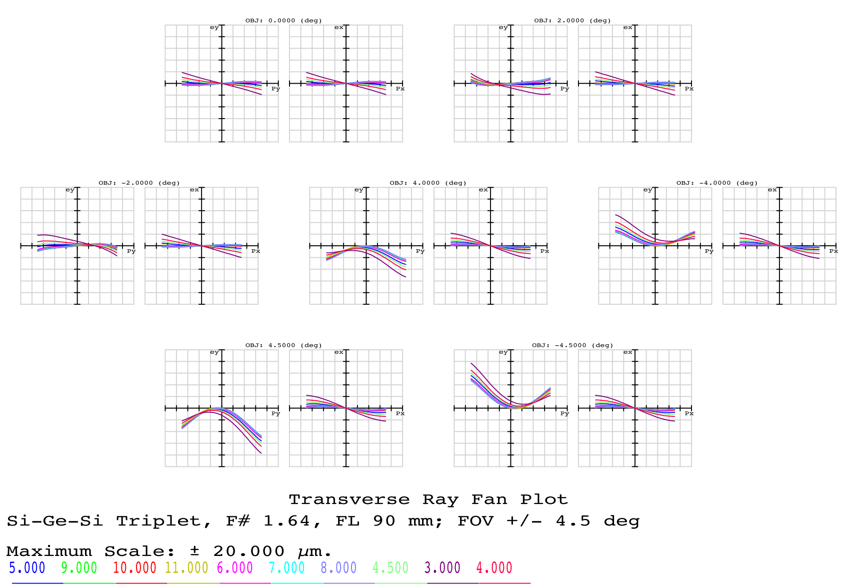

Fig. 8. Transverse ray fan plots for the Si–Ge–Si triplet lens over the full FOV. The maximum plot scale is ± 20 µm. The aberration plots are calculated in the image plane.

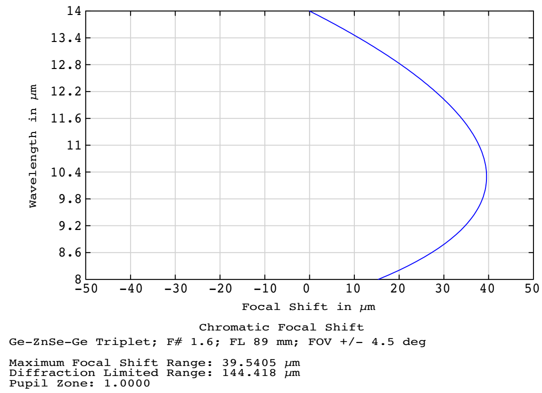

Fig. 10. Plot showing the focal shift for the Ge–ZnSe–Ge triplet lens as function of wavelength over the spectral range 8–14 µm (maximum focal shift range = 39.54 µm).

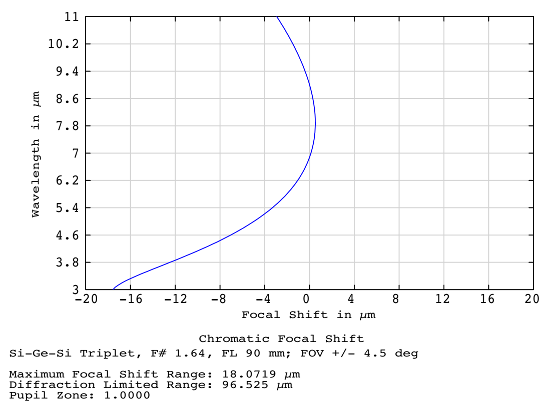

Fig. 11. Plot showing the focal shift for the Si–Ge–Si triplet lens as function of wavelength over the spectral range 3–11 µm (maximum focal shift range = 18.07 µm).

Additionally, as shown in Fig. 4 the calculated Strehl ratio for the Ge–ZnSe–Ge triplet design is 0.983. Similar Huygens PSF plot is calculated for the Si–Ge–Si triplet design with Stehl ratio peaking at 0.979. At 80% fraction of enclosed energy the focused spot radius from the beam centroid is 18 µm for the Ge–ZSe–Ge lens triplet design (shown in Fig. 5) and 16 µm for the Si–Ge–Si triplet lens design (shown in Fig. 6). The calculated Airy disk radius for the Ge–ZnSe–Ge and Si–Ge–Si triplet lens designs is 27.43 and 17.98 µm, respectively. Thus, the focused spot size in the image plane for each triplet lens design is less than the Airy disk diameter. The transverse ray fan plots for the Ge–ZnSe–Ge and Si–Ge–Si lens designs are depicted in Figs. 7 and 8. Figs. 7 and 8 depict aberrations balanced and well corrected Ge–ZnSe–Ge and Si–Ge–Si triplet photographic lens designs. For an aberration-free lens system the curves would be straight lines coincident with the horizontal axis.

Moreover, the calculated wave front maps at the image plane for the Ge–ZnSe–Ge and Si–Ge–Si triplet lens designs suggest that the RMS WFE is 0.0092 and 0.0035 waves, respectively. The wave front map for Ge–ZnSe–Ge triplet lens design in the image plane is shown in Fig. 9. As illustrated in Figs. 10 and 11, the calculated maximum focal shift for the Ge–ZnSe–Ge triplet (spectra band: 8–14 µm) and for the Si–Ge–Si lens (spectral band: 3–11 µm) is 39.54 and 18.07 µm, respectively.

Fig. 12 illustrates the field curvature (the distance from the image surface to the paraxial image surface as a function of field coordinates) and distortion for the Ge–ZnSe–Ge triplet lens design. Likewise, the calculated field curvature and distortion for the Si–Ge–Si triplet lens are shown in Fig. 13. The field curvature plots for each triplet lens show that the field curvature gets worse with

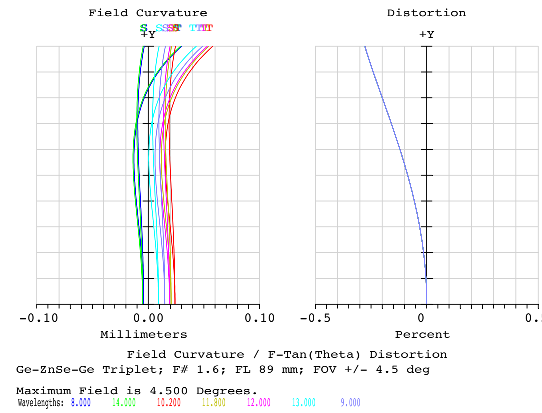

Fig. 12. Graphs showing the field curvature and distortion plots for the Ge–ZnSe–Ge triplet lens design. The field curvature plot represents the distance from the image surface to the paraxial image surface as a function of field coordinates.

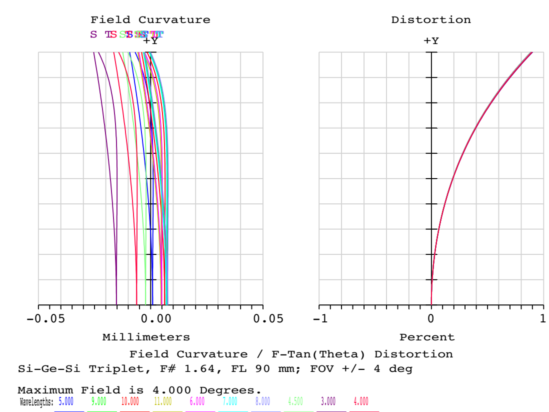

Fig. 13. Graphs showing the field curvature and distortion plots for the Si–Ge–Si triplet lens design.

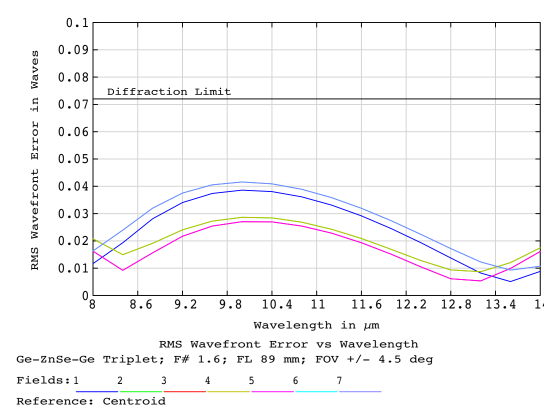

Fig. 14. Plot depicting the Ge–ZnSe–Ge triplet lens RMS wave front error versus wavelength (8–14 µm).

the increase in the value of the field and away from the center. The worst field curvature for both lens designs is observed at the maximum FOV. As noted in Figs. 12 and 13, the calculated distortion for the Ge–ZnSe–Ge and Si–Ge–Si triplets is −0.278 and 1.189%, respectively.

Lastly, as illustrated in Fig. 14 the Ge–ZnSe–Ge triplet lens RMS wave front is below the diffraction limit over the spectral range 8–14 µm, whereas, as shown in Fig. 15, the Si–Ge–Si triplet lens RMS wave front is below the diffraction limit over the spectral range 3–11 µm. However, the Si–Ge–Si triplet lens performance is near diffraction-limited in the spectral band below 3.8 µm.

	Ge–ZnSe–Ge	Si–Ge–Si
Wavelength range	8–14 μm	3–11 μm
Focal length	89.08 mm	90.04 mm
Total track	114.85 mm	162.18 mm
Total mass	138.87 g	164.79 g
F/#	1.60	1.64
FOV	+/−4.5°	+/−4.5°
FFT MTF @50% Modulation	20.0 cycles/mm	26.5 cycles/mm
PSP	0.983	0.979
RMS WFE	0.0092 waves	0.0035 waves
Airy disc radius	27.43 μm	17.98 μm
Beam radius from centroid (encircled energy at 80%)	18 μm	16 μm
RMS spot radius at FOV = 0°	10.29 μm	1.092 μm
RMS spot radius at FOV = 4.5°	8.38 μm	4.64 μm
Max focal shift at 20 °C	39.54 μm	18.07 μm
Max distortion at 20 °C	−0.28%	1.19%

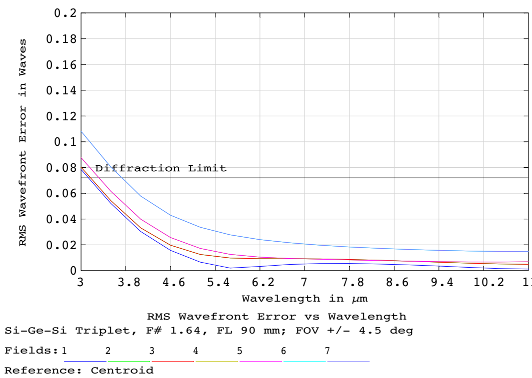

Fig. 15. Plot depicting the Si–Ge–Si triplet lens RMS wave front error versus wavelength (3–11 μm).

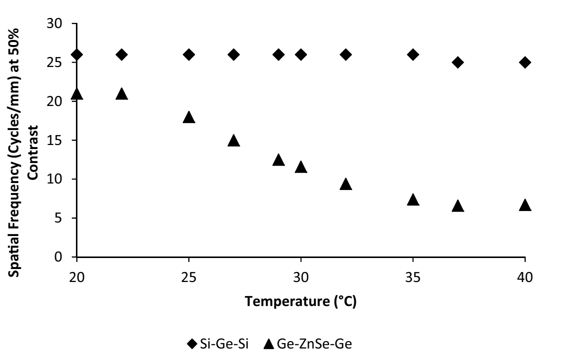

Fig. 16. Plot showing the spatial frequency variation at 50% modulation over the temperature range 20–40°C for the Si–Ge–Si and Ge–ZnSe–Ge triplet designs.

Finally, Fig. 16 depicts the calculated spatial frequency at 50% contrast modulation over the temperature range 20–40 °C for the two triplet lens designs. Clearly, the Ge–ZnSe–Ge triplet lens design is more susceptible to temperature variations, which lead to degradation in the quality of the formed image as the ambient temperature increases.

4. Conclusions

Based on the results presented in this article the following conclusions can be drawn:

1. The Si–Ge–Si triplet lens design can be used for the MWIR and LWIR spectral bands, whereas the Ge–ZnSe–Ge triplet lens can be used only for the LWIR spectral band.
2. The total length of the Ge–ZnSe–Ge triplet lens is shorter than the Si–Ge–Si triplet lens by 47.33 mm.
3. The mass of the Ge–ZeSe–Ge triplet lens is approximately 16% less than the Si–Ge–Si triplet lens.
4. The MTF modulation for the Si–Ge–Si triplet lens is better than the Ge–ZnSe–Ge lens by approximately 25% at 20 °C.
5. The RMS spot radius for the Si–Ge–Si triplet is smaller than the Ge–ZnSe–Ge triplet by a factor of 10 at FOV = 0° and by a factor of 2 at FOV = 4.5°.
6. The image distortion for the Ge–ZeSe–Ge triplet lens is less than the Si–Ge–Si triplet lens by approximately a factor of 4.
7. The image quality of the Si–Ge–Si triplet lens is more stable over the temperature range 20–40 °C than the Ge–ZnZe–Ge triplet lens.

A summary for the performance of the Ge–ZnSe–Ge and Si–Ge–Si air-spaced triplet lens designs is tabulated above.

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