Optical filters dimensions and thermal operation conditions impact on its transmission considerations in near infrared (NIR) optical spectrum transmission region

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We study the different optical filters design considerations over wide range of the operation conditions in near infrared optical spectrum transmission region. There are many operating conditions parameters describing optical filter properties such as the amount absorbed electromagnetic radiation which depends on the operating signal wavelength; the amount of the absorbing material in the filter thickness; and the absorption coefficient of the material at that wavelength. Filter modulation depth, filtration signal quality, filter delay time, filter bit error rate, and filter correction are the major interesting performance parameters in the current study. Best candidate materials based optical filters are used which namely barium fluoride (BaF_2), and zinc selenide (ZnSe) and compared with their measured results by using silicon optical filter. Our results are validated against published experimental studies and show a good agreement and matching.

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1. Introduction

Wavelength division multiplexing (WDM) systems are evolving from point to point systems to transparent optical networks, in which wavelength channels are routed without optoelectronic conversion. All optical WDM networks with add drop, routing and cross connecting capabilities include several wavelength selective components. The concatenation of optical filters makes the system susceptible to filter pass band misalignments arising from device imperfections, temperature variation and aging. The emission spectrum of the laser source may also be misaligned with the effective center frequency of the optical filters owing to manufacturing tolerances, aging, or operating conditions (for example temperature). Performance degradation in WDM systems may arise owing to optical filter misalignments and concatenation, combined with laser misalignments and chirp [1-3]. Another important degradation factor is the reduction of the filters bandwidth due to operation conditions and aging. Filtering in the optical domain can be useful for many systems in which data is modulated on an optical carrier. In the telecom world, applications can be found in WDM channel add-drop filters and gain flattening filters [4, 5]. For analog signal processing at radio frequency (RF), microwave photonic filters can have advantages over all-electronic systems due to their wide tunability, programmability, and immunity to electromagnetic interference. For example, radio-over-fiber (RoF) systems that employ an array of remote antennas benefit from the low loss transmission properties of optical fiber, thus opening up the possibility of pre-filtering in the optical domain before analog-to-digital conversion. In particular, radar systems can benefit from the ultra-wide bandwidth of a tunable optical filter in channelizing and matched filter applications [6].

System performance depends greatly on the accuracy with which optical filter responses are synthesized. For example, an ideal bandpass filter has a flat passband, high extinction, fast roll-off, and is linear-time-invariant (LTI). Optical fiber and bulk optical component based photonic filters suffer from thermal and mechanical instability, and are therefore limited mostly to the incoherent regime, which has significant performance drawbacks [7-9]. Size, weight, power, and cost are also an issue with bulk optical systems. Monolithic integration offers a stable, compact scheme for construction of filter geometries, and recently many filters have been demonstrated in various integration platforms to realize both telecom and microwave photonic filters [10]. Integration in passive systems (those without optical gain) relies on low loss waveguides to maintain filter shape and minimize insertion loss. Silicon photonics and polymer waveguide photonics are two such solutions [11]. However, generating optimal filter shapes in such systems depends strongly on setting waveguide coupling values accurately and creating extremely low loss waveguides. Furthermore, these systems are ultimately limited in complexity by accrued loss, which degrades the system dynamic range [12].

The paper is organized in the following sections. Section II has explained the mathematical model equations for optical filters in more details. Section III has presented the simulation results and performance evaluation of different optical filters type based on fabrication material. Finally, section IV has presented the summary of design parameters considerations for different optical filters under the same operating parameters.

2. Optical filter model

All materials will absorb radiation in some parts of the electromagnetic spectrum. The amount of absorption depends on the wavelength, the amount of absorbing material in the radiation path, and the absorption of that material at that wavelength. Materials that absorb some visible wavelengths appear colored. As a beam of light passes through an absorbing medium [12], the amount of light absorbed is proportional to the intensity of incident light times the absorption coefficient. Consequently, the intensity of an incident beam drops exponentially as it passes through the absorber. Therefore the filter signal attenuation and filter transmission are often expressed as the following formulas [13]:

$$A_F = \exp\left(\frac{2\pi}{\lambda} n_{eff}\, d\right) \tag{1}$$

$$T_F = \exp\left(-A_F\, L_F\right) \tag{2}$$

Where d is the filter thickness, L_F is the filter length, λ is the operating optical signal wavelength, and n_{eff} is the effective filter refractive index which is given by [14]:

$$n_{eff} = n - \lambda \frac{dn}{d\lambda} \tag{3}$$

Where n is the refractive index of the optical filter relative to air which can be expressed with Sellemier glass formula as [4]:

$$n = \sqrt{1 + \frac{A_1 \lambda^2}{\lambda^2 - A_2^2} + \frac{A_3 \lambda^2}{\lambda^2 - A_4^2} + \frac{A_5 \lambda^2}{\lambda^2 - A_6^2}} \tag{4}$$

Where the Semellier coefficients for different materials based optical filters as barium fluoride (BaF_2), and zinc selenide (ZnSe) are adjusted and recast as shown in Table 1.

Table 1. Sellemier coefficients for materials based optical filters [4].

Coefficients	Different materials based Optical filters	
	Barium Fluoride (BaF_2)	Zinc Selenide (ZnSe)
A_1	1.0063 (T/T_0)	4.45814 (T/T_0)
A_2	0.07559 $(T/T_0)^2$	0.20086 $(T/T_0)^2$
A_3	0.143785 (T/T_0)	0.4672 (T/T_0)
A_4	0.13236 $(T/T_0)^2$	0.39137 $(T/T_0)^2$
A_5	3.7884 (T/T_0)	2.89566 (T/T_0)
A_6	46.17 $(T/T_0)^2$	47.136 $(T/T_0)^2$

The filter correction factor P which can be defined as the following formula [14, 15]:

$$P = 1 - 2\left(\frac{n-1}{n+1}\right)^2 + \left(\frac{n-1}{n+1}\right)^4, \tag{5}$$

Therefore filter correction factor percentage is given by the following expression:

$$P(\%) = \left[1 - 2\left(\frac{n-1}{n+1}\right)^2 + \left(\frac{n-1}{n+1}\right)^4\right] x100\%, \tag{6}$$

The reflection loss R is also dependent on the operating optical wavelength and can be calculated as follows [15, 16]:

$$R = \left(\frac{n-1}{n+1}\right)^2 \tag{7}$$

As optical density increases, the amount of light blocked by the filter by reflection or absorption increases. The most important point to note is that optical density is additive. As well as the transmission modulation depth (TMD) is given by:

$$TMD = 10\,\log_{10}\left(\frac{1+\sqrt{P}}{1-\sqrt{P}}\right), \text{ dB} \tag{8}$$

The optical filtering signal quality, Q can be expressed as a function of operating optical signal wavelength λ and filter full width at half maximum as the following formula [17]:

$$Q\,(dB) = 10\log_{10}\left[\frac{\lambda}{FWHM}\right] \tag{9}$$

Where FWHM is the full width at half maximum which is applied to such phenomena as the duration of pulse waveforms and the spectral width of sources used for optical communications and the resolution of spectrometers and can be estimated as the following formula [17]:

$$FWHM = 0.635\, BW_F \tag{10}$$

Where BW_F is the transmitted signal bandwidth with non return to zero coding (NRZ) which is given by [18]:

$$BW_F = \frac{0.7}{\tau} \tag{11}$$

Where τ is the total pulse broadening through optical filter which can be given by [18]:

$$\tau = L_F \, D_m \, \Delta\lambda \tag{12}$$

Where Δλ is the spectral linewidth of the optical source in nm, and D_m is the material dispersion coefficient based optical filter which can be estimated as in Ref. [18]. Moreover the bit error rate (BER) is considered an important figure of merit for optical signal filtration; all designs are based to adhere to that quality. BER in optical communication system is calculated by the following equation [19]:

$$BER = 0.5\, erfc\left(\frac{Q}{\sqrt{2}}\right) \tag{13}$$

As well as the filter delay time can be estimated by the following equation [13]:

$$\gamma = \frac{n \, L_F}{c} \tag{14}$$

3. Performance analysis

In the present study, the different optical filters design considerations are deeply investigated in near infrared optical spectrum transmission region over wide range of the affecting operating parameters such as filter dimensions and thermal operation conditions as shown in Table 2.

Table 2. List of operating parameters used in the simulation [4, 7, 13, 15, 16].

Parameter	Definition	Value and units
λ	Near infrared optical wavelength	1550 nm
T	Ambient temperature	25 °C-325 °C
T_0	Room temperature	25 °C
d	Filter thickness	2 mm-10 mm
L_F	Filter length	10 mm-50 mm
Δλ	Source spectral line width	0.1 nm

Based on the model equations analysis, assumed set of the operating parameters, and the set of the series of the Figs. (1-15), the following facts are assured:

i) Fig. 1 has assured that filter refractive index increases with increasing ambient temperature for both selected materials based optical filters. It is indicated that zinc selenide optical filter refractive index is larger than barium fluoride optical filter under the same spectral and thermal operation conditions.

ii) Figs. (2-4) have indicated that filter signal attenuation increases with increasing filter thickness for both selected candidate materials based optical filters. As well as it is theoretically found that zinc selenide optical filter signal attenuation is larger than barium fluoride optical filter under the same filter dimensions (length and thickness), spectral and thermal operation conditions. Our theoretical results are complete matching with their experimental results [15, 16].

iii) As shown in Figs. (5-7) have demonstrated that filter transmission decreases with increasing filter length for both selected candidate materials based optical filters. As well as it is theoretically found that zinc selenide optical filter signal transmission is lower than barium fluoride optical filter under the same filter dimensions (length and thickness), spectral and thermal operation conditions. Moreover, our theoretical results are complete matching with their experimental results [15, 16].

iv) Figs. (8-10) have assured that filter correction factor, filter transmission modulation depth decrease and filter reflection loss increases with increasing ambient temperature for both selected materials based optical filters. It is indicated that zinc selenide optical filter performance is lower than barium fluoride optical filter under the same spectral and thermal operation conditions.

v) Figs. (11, 12) have indicated that filter signal quality decreases and filter bit error rate increases with increasing ambient temperatures for both selected materials based optical filters. It is indicated that zinc selenide optical filter signal transmission quality is lower than barium fluoride optical filter under the same filter dimensions (length and thickness), spectral and thermal operation conditions.

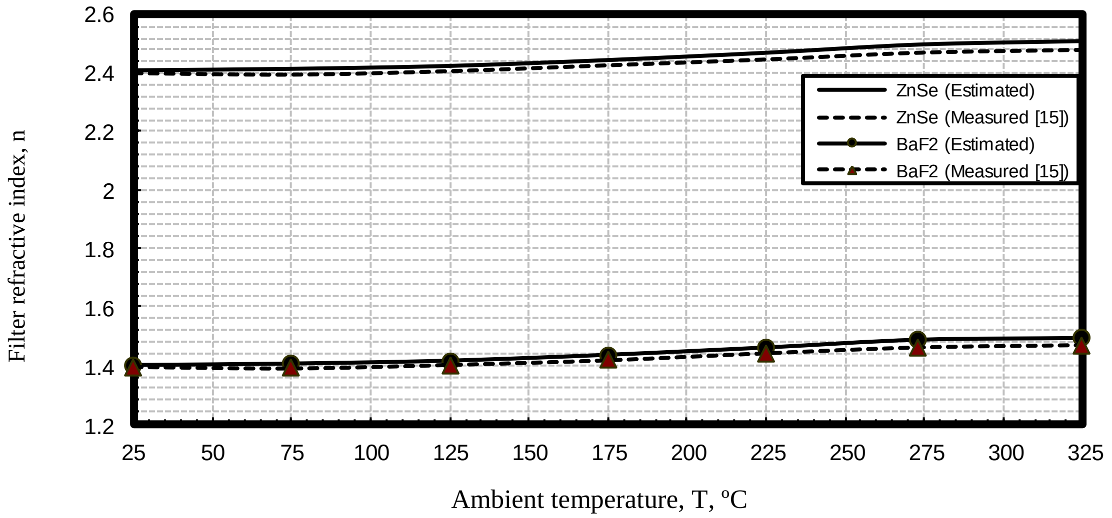

Fig. 1. Filter refractive index in relation to ambient temperature for different materials based optical filters at the assumed set of the operating parameters.

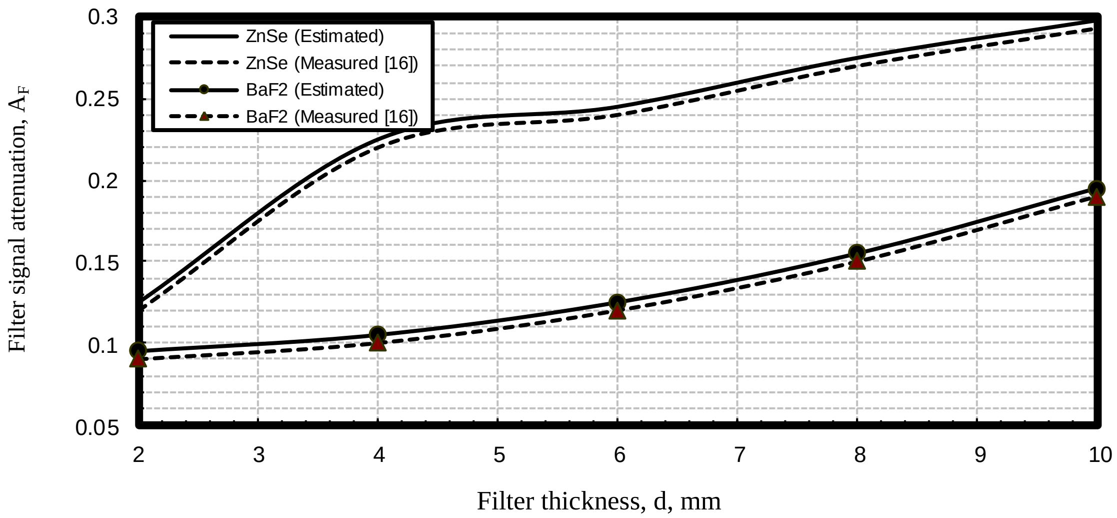

Fig. 2. Variations of filter signal attenuation versus variations of filter thickness with room temperature (T_0=25 ºC) and filter length (L_F=10 mm) for different materials based optical filters at the assumed set of the operating parameters.

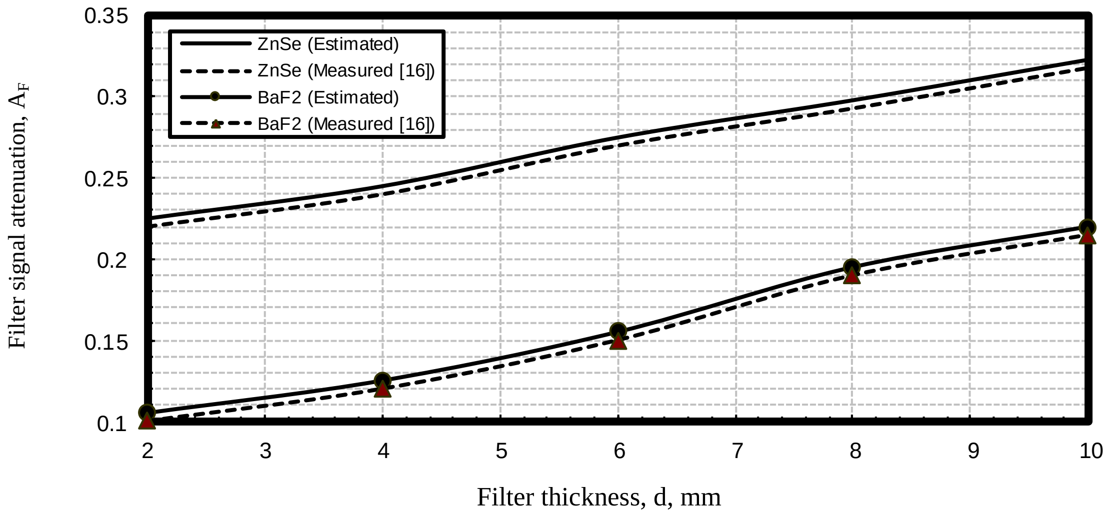

Fig. 3. Variations of filter signal attenuation versus variations of filter thickness with ambient temperature (T=175 ºC) and filter length (L_F=10 mm) for different materials based optical filters at the assumed set of the operating parameters.

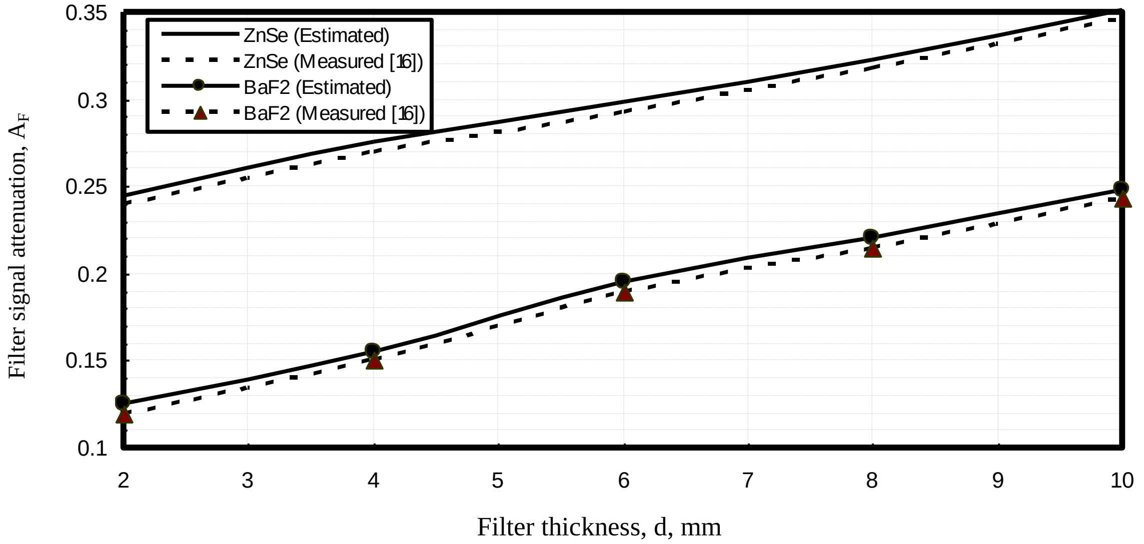

Fig. 4. Variations of filter signal attenuation versus variations of filter thickness with ambient temperature (T=325 ºC) and filter length (L_F=10 mm) for different materials based optical filters at the assumed set of the operating parameters.

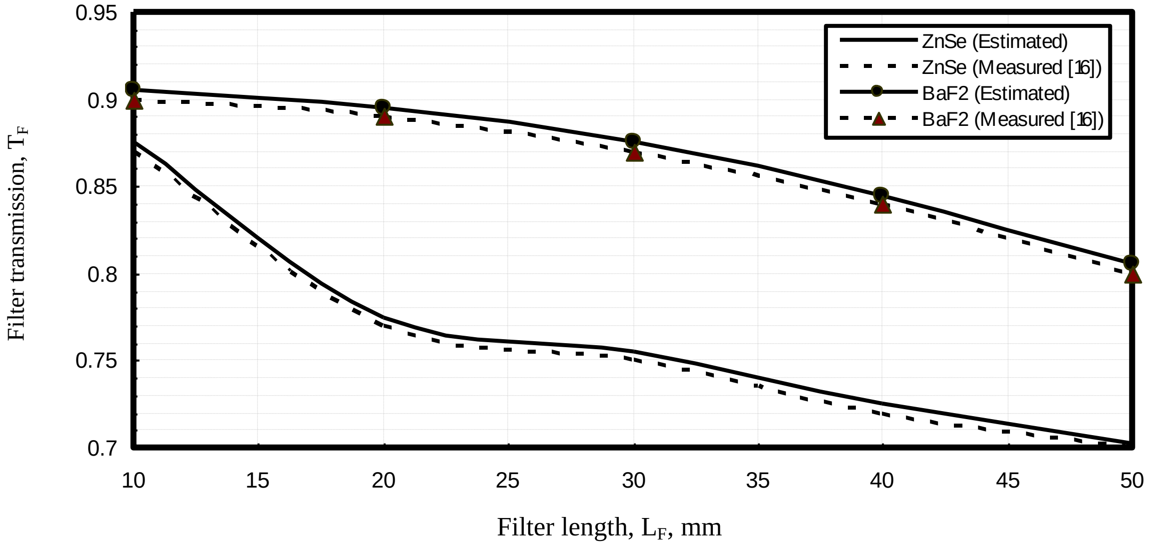

Fig. 5. Filter transmission in relation to filter length with room temperature (T_0=25 ºC) and filter thickness (d=2 mm) for different materials based optical filters at the assumed set of the operating parameters.

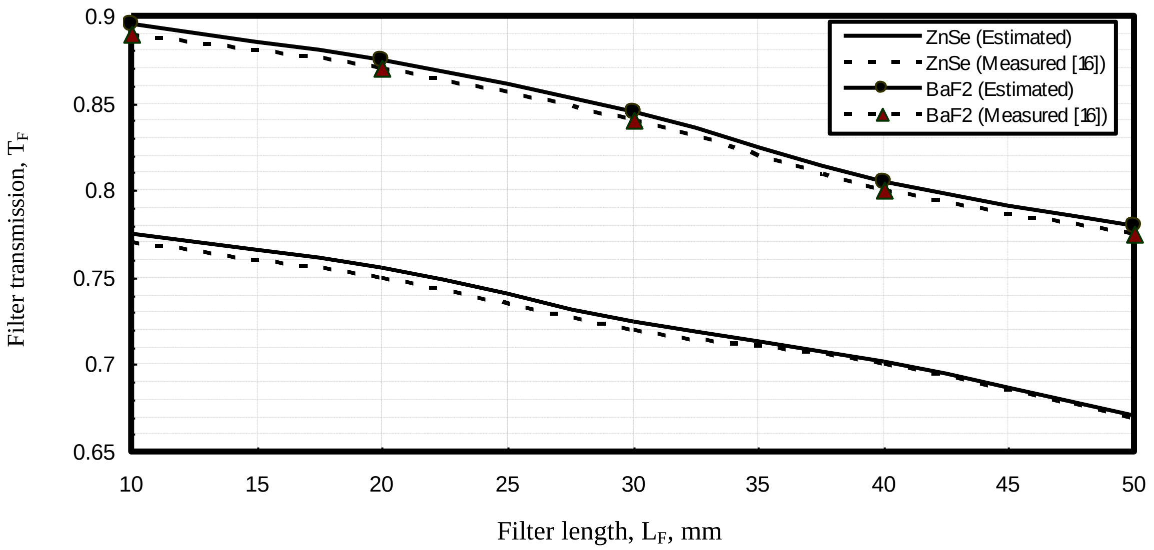

Fig. 6. Filter transmission in relation to filter length with ambient temperature (T=175 ºC) and filter thickness (d=2 mm) for different materials based optical filters at the assumed set of the operating parameters.

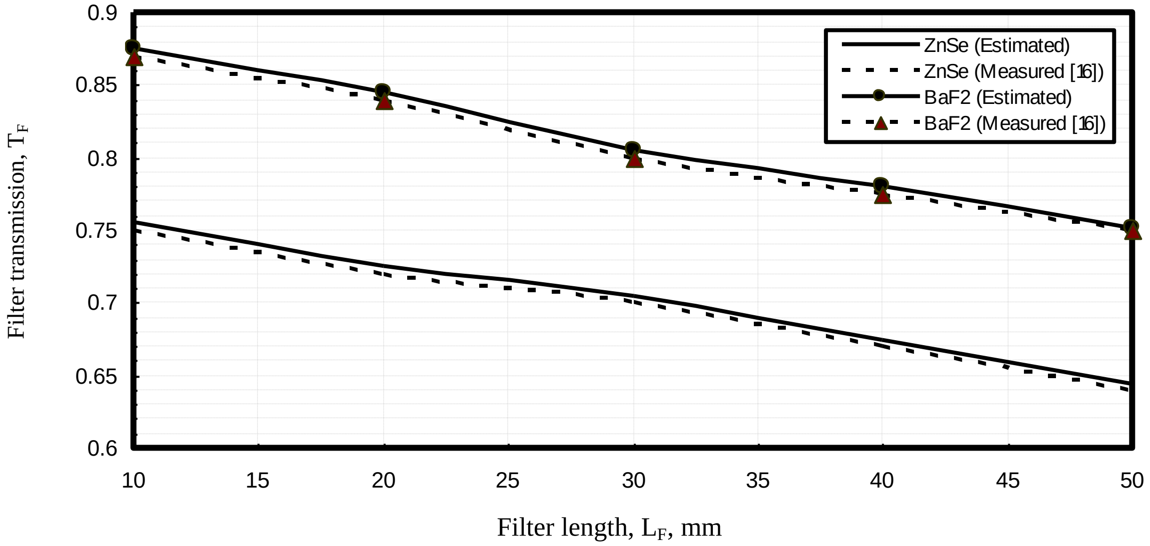

Fig. 7. Filter transmission in relation to filter length with ambient temperature (T=325 ºC) and filter thickness (d=2 mm) for different materials based optical filters at the assumed set of the operating parameters.

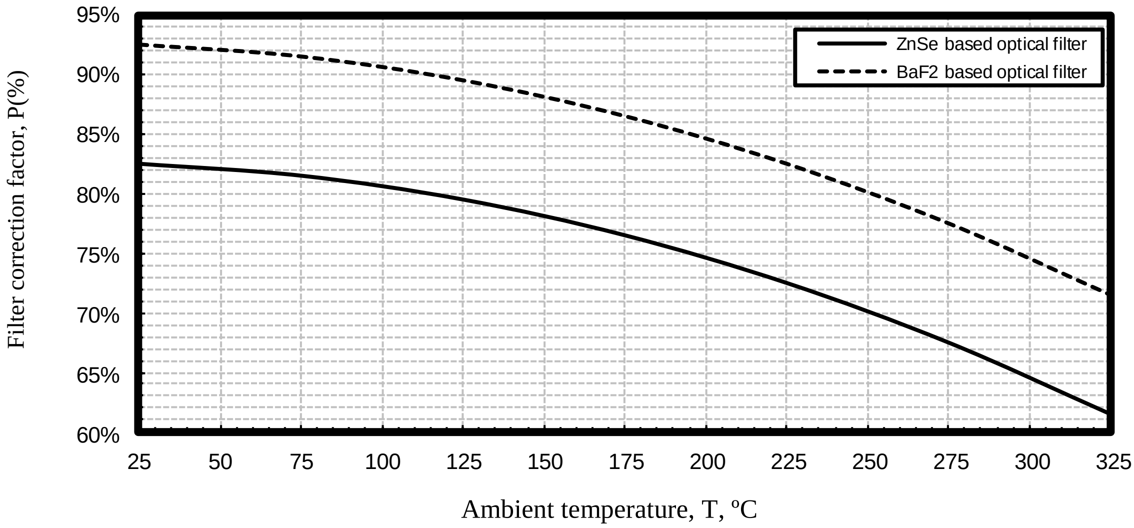

Fig. 8. Filter correction factor in relation to ambient temperature for different materials based optical filters at the assumed set of the operating parameters.

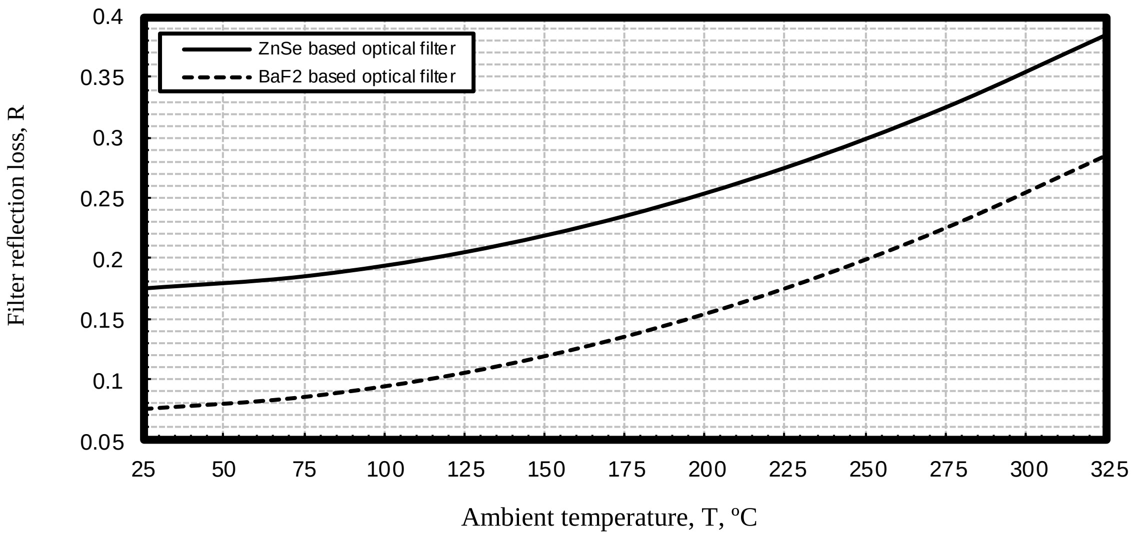

Fig. 9. Filter reflection loss in relation to ambient temperature for different materials based optical filters at the assumed set of the operating parameters.

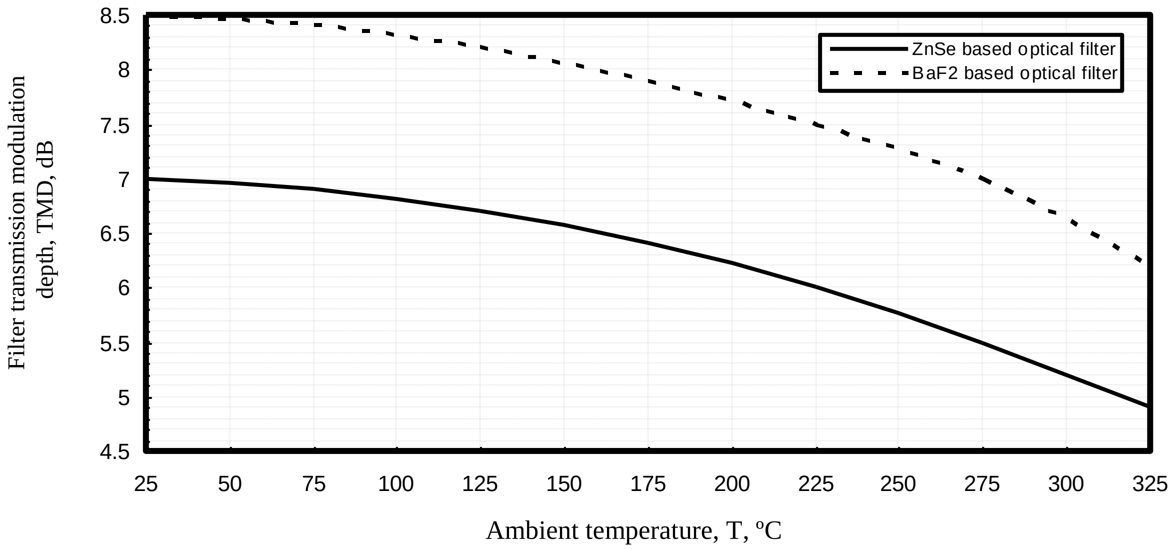

Fig. 10. Filter transmission modulation depth in relation to ambient temperature for different materials based optical filters at the assumed set of the operating parameters.

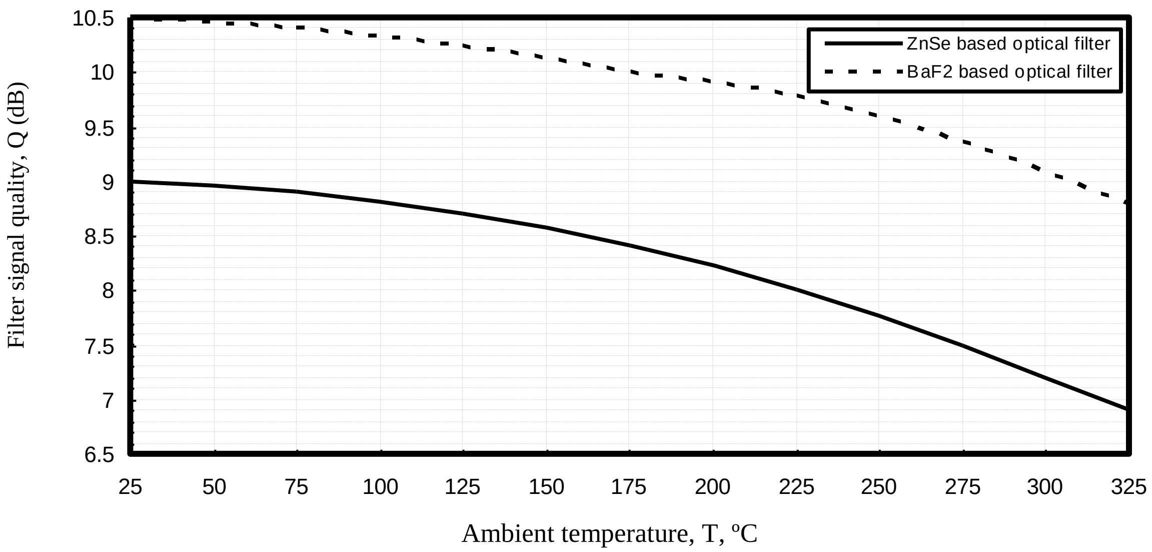

Fig. 11. Filter signal quality in relation to ambient temperature with filter length (L_F==10 mm) for different materials based optical filters at the assumed set of the operating parameters.

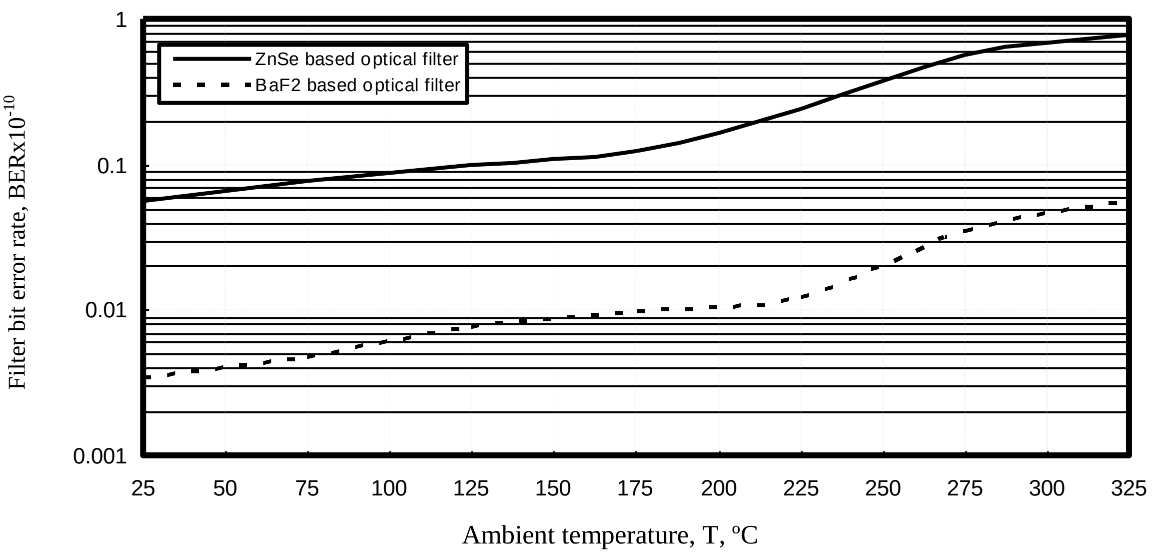

Fig. 12. Filter bit error rate in relation to ambient temperature with filter length (L_F==10 mm) for different materials based optical filters at the assumed set of the operating parameters.

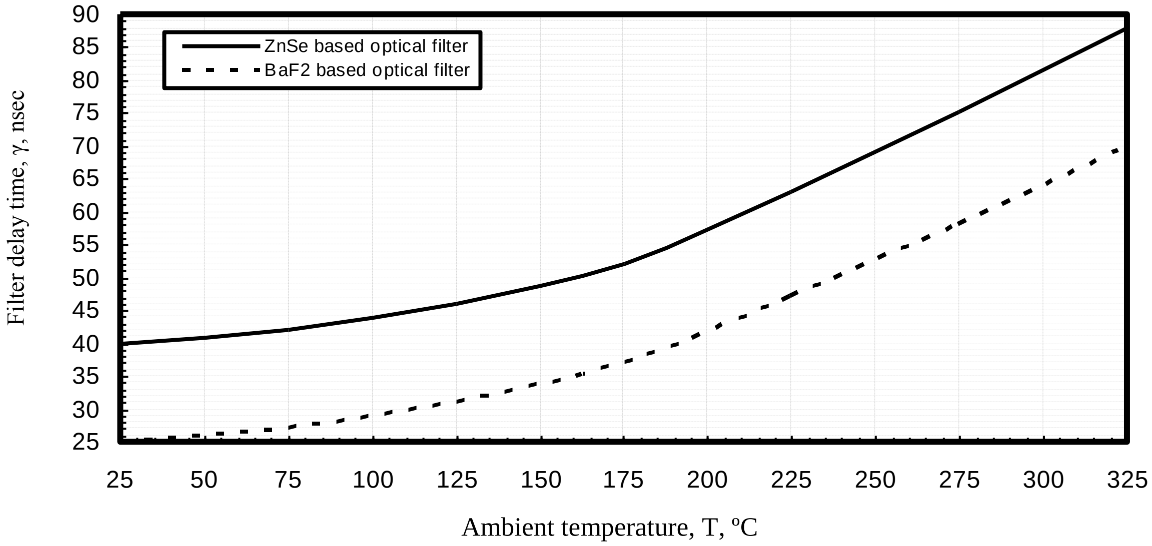

Fig. 13. Filter delay time in relation to ambient temperature with filter length (L_F==10 mm) for different materials based optical filters at the assumed set of the operating parameters.

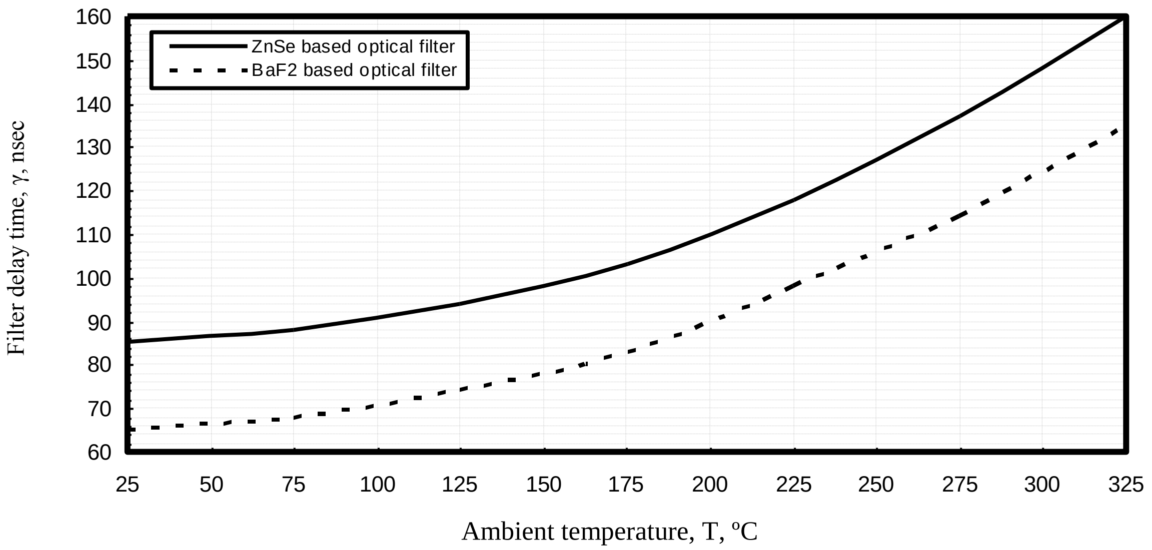

Fig. 14. Filter delay time in relation to ambient temperature with filter length (L_F=30 mm) for different materials based optical filters at the assumed set of the operating parameters.

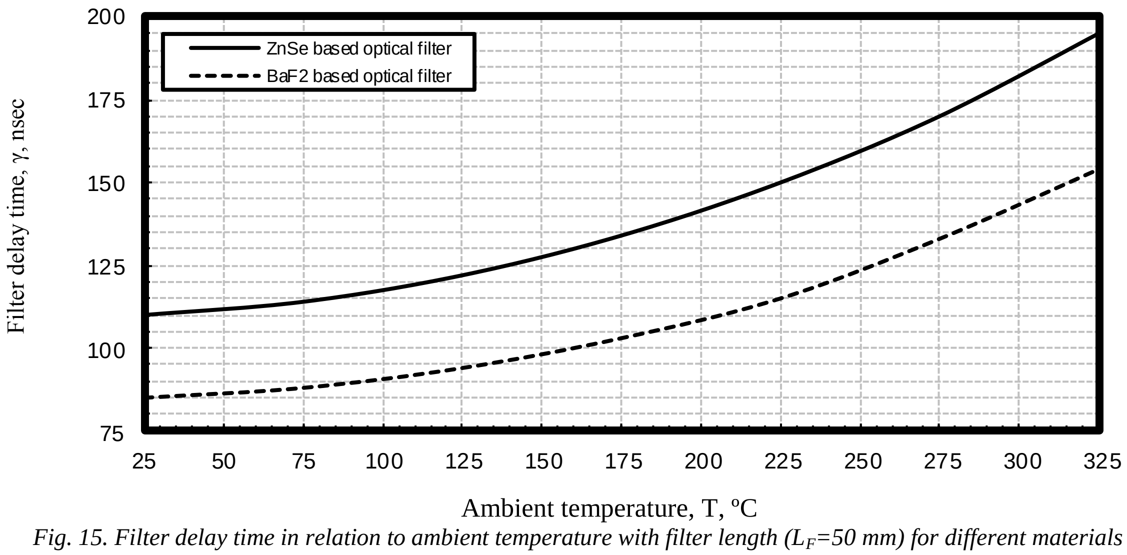

Fig. 15. Filter delay time in relation to ambient temperature with filter length (L_F=50 mm) for different materials based optical filters at the assumed set of the operating parameters.

vi) As shown in Figs. (13-15) have demonstrated that filter delay time increases with increasing both ambient temperatures and filter length for both selected materials based optical filters. It is indicated that zinc selenide optical filter delay time is larger than barium fluoride optical filter under the same spectral and thermal operation conditions.

4. Conclusions

In a summary, we have deeply investigated optical filters dimensions and thermal operation conditions impact on its transmission considerations in near infrared optical spectrum transmission region around 1550 nm. It is theoretically found that the dramatic effects of filter dimensions (filter length and filter thickness) on the performance parameters of optical filters under study and validation with measured results for filter refractive index, filter attenuation and filter transmission under the same spectral and thermal operation conditions and shown a compete matching between our theoretical results with their measured results [4, 15, 16]. We have compared our theoretical results for ZnSe and BaF_2 optical filters with common Silicon optical filters [15, 20, 21] as listed in Table 3 below.

Table 3. Compared our theoretical results with their measured results for Silicon optical filters.

Performance parameters	λ=1550nm, room temperature (T_0=25 ºC), filter length (L_F=10 mm), and filter thickness (d=2mm)		Silicon based optical filter [15, 20, 21]
	BaF_2 based optical filter	ZnSe based optical filter	
Refractive index, n	1.4	2.41	3.45 [15]
Filter signal attenuation, A_F	0.095	0.125	0.165 [20, 21]
Filter transmission, T_F	0.905	0.875	0.835 [20, 21]
Filter reflection loss, R	0.075	0.175	0.202 [15, 16]
	Proposed performance parameters estimation based on operating parameters in Table 2		
Filter correction factor, P(%)	92.5 %	82.5 %	78.65 %
Transmission modulation depth, TMD (dB)	8.5	7	6
Filter signal quality, Q (dB)	10.5	9	8
Bit error rate, BERx10^{-10}	0.00345	0.0564	0.06125
Filter delay time, γ, nsec	25	40	50

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