Applications of Arrayed Waveguide Grating (AWG) in Passive Optical Networks

Abd El–Naser A. Mohammed[1], Ahmed Nabih Zaki Rashed[2*], and Abd El–Fattah A. Saad[3]

[1,2,3]Electronics and Electrical Communication Engineering Department
Faculty of Electronic Engineering, Menouf, Menoufia University, 32951, EGYPT
abd_elnaser6@yahoo.com, ahmed_733@yahoo.com

Abstract

In the present paper, we have investigated two characteristics of three different waveguides employed in arrayed waveguide grating (AWG) in passive optical networks (PON) where rates of variations are processed. Both the thermal and the spectral effects are taken into account. The waveguides are made of Lithium Niobate, germania-doped silica, and Polymethyl metha acrylate (PMMA) polymer. The thermal and spectral sensitivities of optical devices are also analyzed. In general, both qualitative and quantitative analysis of the temporal and spectral responses of AWG and sensitivity are parametrically processed over wide ranges of the set of affecting parameters.

Keywords: *PONs, Arrayed Waveguide Grating (AWG), Lithium Niobate ($LiNbO_3$) material, Silica-doped material, Polymethyl-metha acrylate (PMMA) Polymer material.*

1. Introduction

Current PON systems are generally based on Time Division Multiplexing (TDM-PON). The key issues in these systems are how to increase [1] their transmission capacity and how to diversify their transmission data. Since video streams are used in the access network [2], broadcast is a very important issue in PON systems. In TDMPON, there are several ways to broadcast data to the Optical Network Units (ONUs): sub-carrier multiplexing technique [3], frequency division multiplexing (FDM) and Time Division technique which multiplexes digital base-band and RF video signals in frequency domain and modulates the mixed signal onto single wavelength [4], and a CWDM-based approach which uses a separate wavelength for video [4]. Meanwhile, new demands from subscribers require more capacity than that of TDM-PONs can provide so that Wavelength Division Multiplexing (WDM) PONs have been proposed [5]. However, it is difficult in WDM-PON architectures to be able to broadcast a data or video stream to all subscribes at once because the output ports of the wavelength selective devices of the Optical Distribution Network (ODN) only passes [6] a specific wavelength channel on each specific port. Therefore, many researchers are now proposing novel solutions for this problem. One way to broadcast data over WDM-PON is to use N×N arrayed waveguide grating (AWG). In this structure, each optical network unit (ONU) receives the main signal along with the broadcast signal, but an extra WDM filter is needed at the ODN to separate the broadcast wavelength. Another way is to use a broadcast and selection method. This system is a simple network architecture [7], but the ONUs of this configuration have a much more complex structure than conventional ONUs. The continuous demand for Internet and telecommunication services is expected to keep driving the development of wavelength division multiplexed (WDM) networks. Wavelength multiplexers and demultiplexers [8], capable of combining and separating different spectral channels, are the key components of WDM network. The planar waveguide based mux/demux devices include arrayed waveguide gratings (AWG) and echelle grating devices. State-of-the-art silica-on-silicon AWGs become prohibitively large for devices with higher channel counts and narrower channel spacing (CS), and the integration of different functions on a single chip is not feasible for practical systems unless the size of the individual functional elements is significantly reduced. Silicon-based photonic waveguide circuits have recently emerged as commercially viable optoelectronic devices. In silicon on-insulator (SOI) waveguide devices [9-11], several orders of magnitude reduction of device size can be achieved as compared to devices based on silica-on-silicon materials. This is possible because of a very high difference in refractive index between the waveguide core (Si, n ~ 3.5) and the surrounding cladding material (typically SiO_2, n ~ 1.5). AWG demultiplexers in SOI platform have been demonstrated [12-13]. Ultra compact AWG devices using silicon wire waveguides have recently been reported, but practical application of similar devices will require substantial improvements in quality of silicon waveguides of sub micrometer cross-sectional dimensions, particularly the sidewall roughness. Since conventional AWG demultiplexers require curved waveguides, the minimum available bend radius, which in turn is determined by the index contrast, sets the lower limit for the device dimensions [14-16]. At the same time, AWG dispersion, and hence minimum achievable CS, is limited by a maximum available length difference between the waveguides in the phased array. Here, a new dispersive element comprising the straight waveguides with sections of modified group index that, if placed in the phase array of a conventional AWG, can enhance dispersion properties of the latter. In the examples shown here [17-19], the group index is modified by changing the waveguide width or by the photonic-band gap effect. Fabrication challenges of such approach are obvious. These difficulties are obviated in our element because waveguide widths can be simply modified by lithography and no additional fabrication steps are required [20].

In the present study, both the thermal and spectral variations of three waveguides made of different materials are deeply and parametrically investigated over wide range of the affecting parameters. Thermal sensitivity and spectral sensitivity are also of major interest in photonic integrated circuits (PIC).

2. Basic Model and Analysis

2.1. Lithium niobate ($LiNbO_3$) material

The investigation of both the thermal and spectral variations of the waveguide refractive index (n) require Sellmeier equation. The set of parameters required to completely characterize the temperature dependence of the refractive-index (n) is given below, Sellmeier equation is under the form [21]:

$$n^2 = A_1 + A_2 H + \frac{A_3 + A_4 H}{\lambda^2 - (A_5 + A_6 H)^2} + \frac{A_7 + A_8 H}{\lambda^2 - A_9^2} - A_{10}\lambda^2 \ , \qquad (1)$$

where λ is the optical wavelength in μm and $H = T^2 - T_0^2$. T is the temperature of the material, K, and T_0 is the reference temperature and is considered as 300 K. The set of parameters of

Sellmeier equation coefficients ($LiNbO_3$) are recast and dimensionally adjusted as below [21]:
A_1=5.35583, A_2=4.629 x 10^{-7}, A_3=0.100473, A_4=3.862 x 10^{-8}, A_5=0.20692, A_6= -0.89 x 10^{-8}, A_7=100, A_8=2.657 x 10^{-5}, A_9=11.34927, and A_{10}=0.01533. Equation (1) can be simplified as:

$$n^2 = A_{12} + \frac{A_{34}}{\lambda^2 - A_{56}^2} + \frac{A_{78}}{\lambda^2 - A_9^2} - A_{10}\lambda^2 \tag{2}$$

where: $A_{12}=A_1+A_2H$, $A_{34}=A_3+A_4H$, $A_{56}=A_5+A_6H$, and $A_{78}=A_7+A_8H$.

Then, the differentiation of Eq. (2) w. r. t λ gives:

$$\frac{dn}{d\lambda} = \left(\frac{-\lambda}{n}\right)\left[\frac{A_{34}}{\left(\lambda^2 - A_{56}^2\right)^2} + \frac{A_{78}}{\left(\lambda^2 - A_9^2\right)^2} + A_{10}\right] \tag{3}$$

Also, the differentiation of Eq. (2) w. r. t T gives:

$$\frac{dn}{dT} = \left(\frac{T}{n}\right)\left[A_2 + \frac{\left(\lambda^2 - A_{56}^2\right)A_4 + 2A_6A_{56}A_{34}}{\left(\lambda^2 - A_{56}^2\right)^2} + \frac{A_8}{\left(\lambda^2 - A_9^2\right)}\right] \tag{4}$$

2. 2. Germania doped silica (GeO_2(x)+SiO_2(1-x)) material

The refractive index of this waveguide is cast as [22]:

$$n^2 = 1 + \frac{B_1\lambda^2}{\lambda^2 - B_2^2} + \frac{B_3\lambda^2}{\lambda^2 - B_4^2} + \frac{B_5\lambda^2}{\lambda^2 - B_6^2} \tag{5}$$

The Sellemier coefficients as a function of temperature, and germania mole fraction, x, as follows:

B_1= 0.691663+0.1107001* x, B_2= $(0.0684043+0.000568306 * x)^2 * (T/T_0)^2$
B_3= 0.4079426+0.31021588 * x, B_4= $(0.1162414+0.03772465 * x)^2 * (T/T_0)^2$
B_5= 0.8974749-0.043311091 * x, and B_6= $(9.896161+1.94577 * x)^2$.

The differentiation of Eq. (5) w. r. t λ gives:

$$\frac{dn}{d\lambda} = -(\lambda/n)\left[\frac{B_1B_2^2}{(\lambda^2 - B_2^2)^2} + \frac{B_3B_4^2}{(\lambda^2 - B_4^2)^2} + \frac{B_5B_6^2}{(\lambda^2 - B_6^2)^2}\right] \tag{6}$$

Also, the differentiation of Eq. (5) w. r. t T yields:

$$\frac{dn}{dT} = \left(-\lambda^2/n\right)\left[\frac{B_1B_2\frac{\partial B_2}{\partial T}}{\left(\lambda^2 - B_2^2\right)^2} + \frac{B_3B_4\frac{\partial B_4}{\partial T}}{\left(\lambda^2 - B_4^2\right)^2} + \frac{B_5B_6\frac{\partial B_6}{\partial T}}{\left(\lambda^2 - B_6^2\right)^2}\right] \quad (7)$$

2. 3. Polymethyl-metha acrylate (PMMA) polymer material

The refractive index of this waveguide is cast as [23]:

$$n^2 = 1 + \frac{C_1\lambda^2}{\lambda^2 - C_2^2} + \frac{C_3\lambda^2}{\lambda^2 - C_4^2} + \frac{C_5\lambda^2}{\lambda^2 - C_6^2} \quad (8)$$

The set of parameters of Sellmeier equation coefficients (PMMA) are recast below [23]:

C_1=0.4963, C_2= 0.0718 (T/T_0), C_3=0.6965, C_4=0.1174 (T/T_0), C_5=0.3223, and C_6=9.237.

where T is the temperature of the material, and T_0 is the reference temperature.

The differentiation of Eq. (8) w. r. t λ gives:

$$\frac{dn}{d\lambda} = -(\lambda/n)\left[\frac{C_1C_2^2}{(\lambda^2 - C_2^2)^2} + \frac{C_3C_4^2}{(\lambda^2 - C_4^2)^2} + \frac{C_5C_6^2}{(\lambda^2 - C_6^2)^2}\right] \quad (9)$$

Also, the differentiation of Eq. (8) w. r. t T yields:

$$\frac{dn}{dT} = \left(-\lambda^2/n\right)\left[\frac{C_1C_2\frac{\partial C_2}{\partial T}}{\left(\lambda^2 - C_2^2\right)^2} + \frac{C_3C_4\frac{\partial C_4}{\partial T}}{\left(\lambda^2 - C_4^2\right)^2} + \frac{C_5C_6\frac{\partial C_6}{\partial T}}{\left(\lambda^2 - C_6^2\right)^2}\right] \quad (10)$$

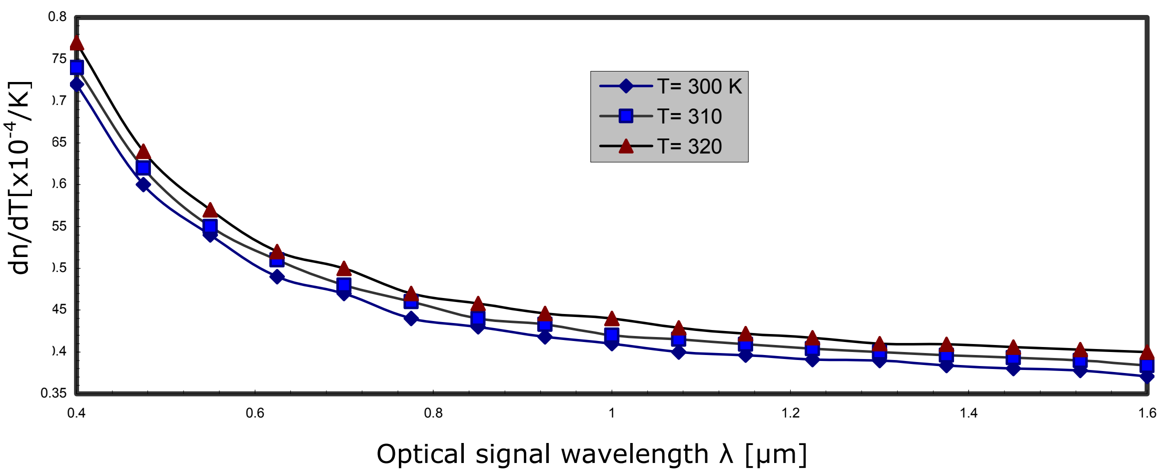
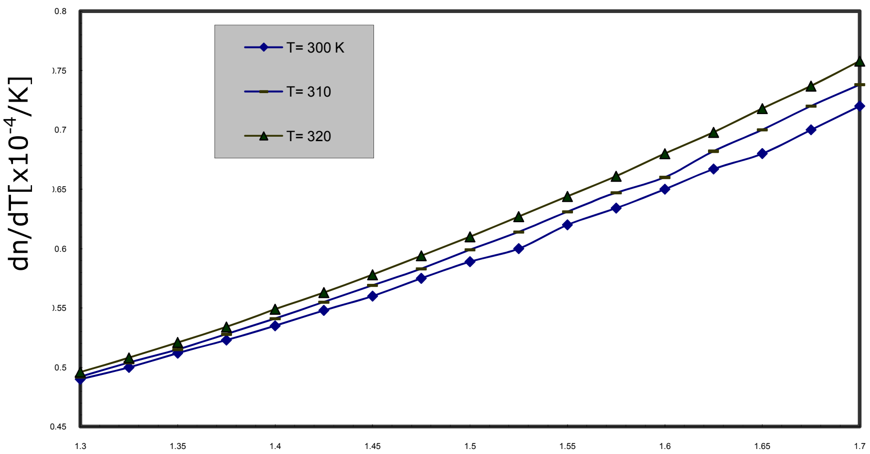
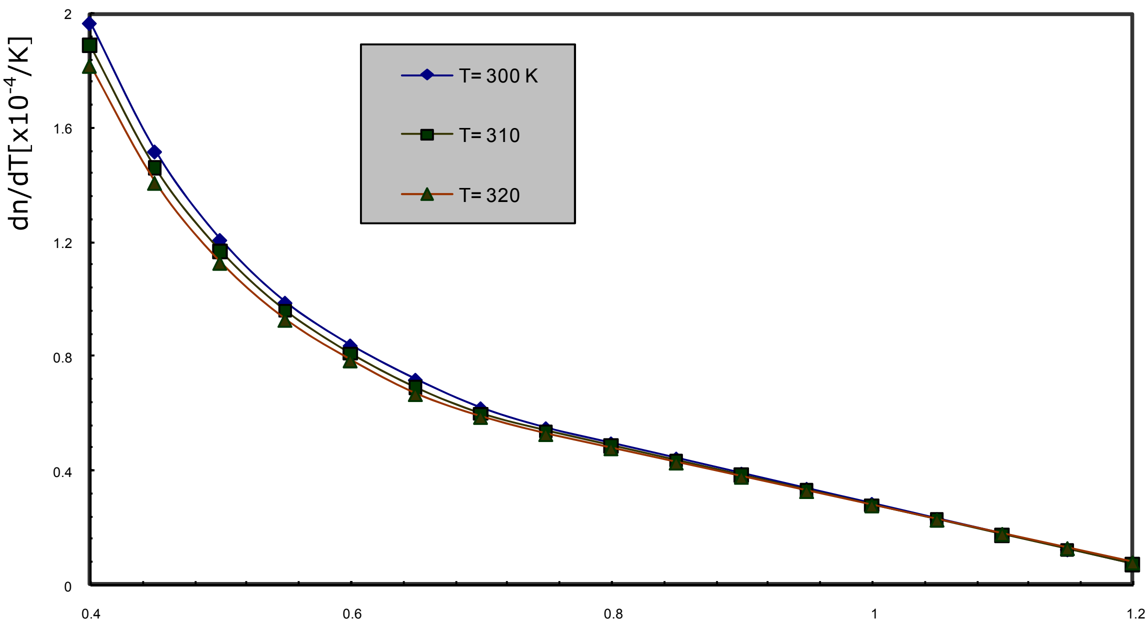


Figure 1. Variation of dn/dT versus wavelength for $LiNbO_3$ material.



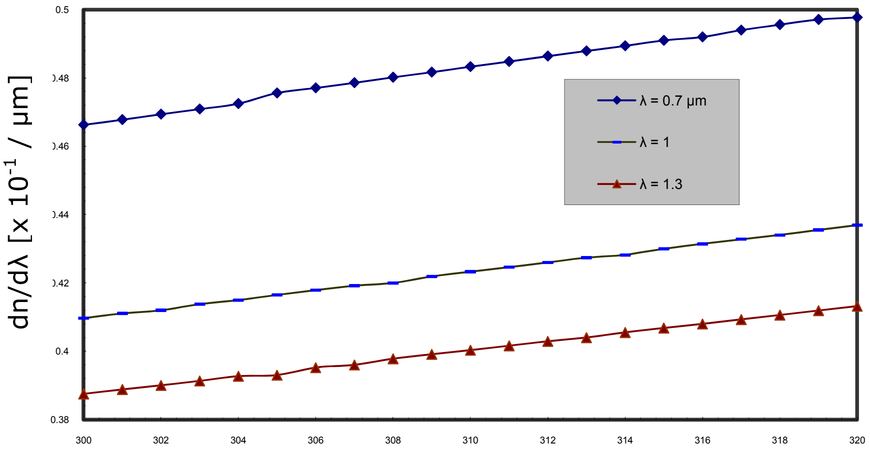
Optical signal wavelength λ [μm]

Figure 2. Variation of dn/dT versus wavelength for Silica- doped material.



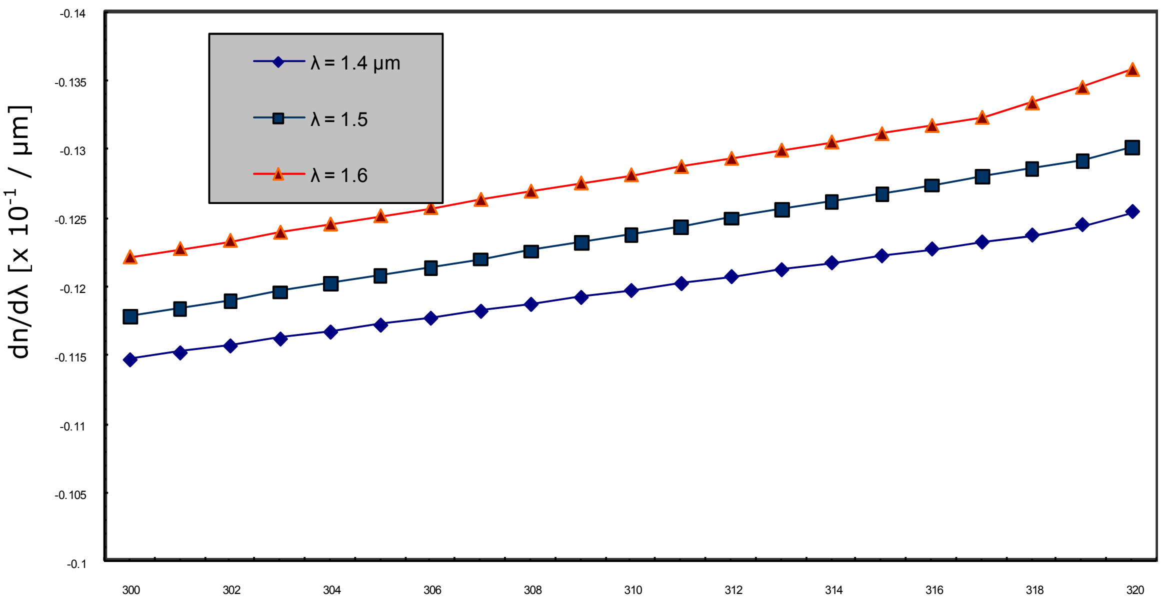
Optical signal wavelength λ [μm]

Figure 3. Variation of dn/dT versus wavelength for PMMA material.



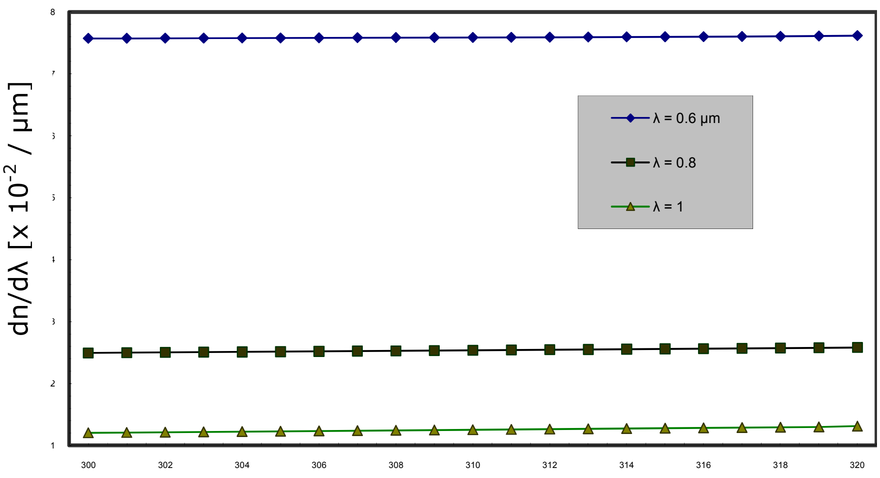
Material temperature T [K]

Figure 4. Variation of dn/dλ versus temperature for $LiNbO_3$ material.



Material temperature T [K]

Figure 5. Variation of dn/dλ versus temperature for Silica-doped material.



Material temperature T [K]

Figure 6. Variation of dn/dλ versus temperature for PMMA material.

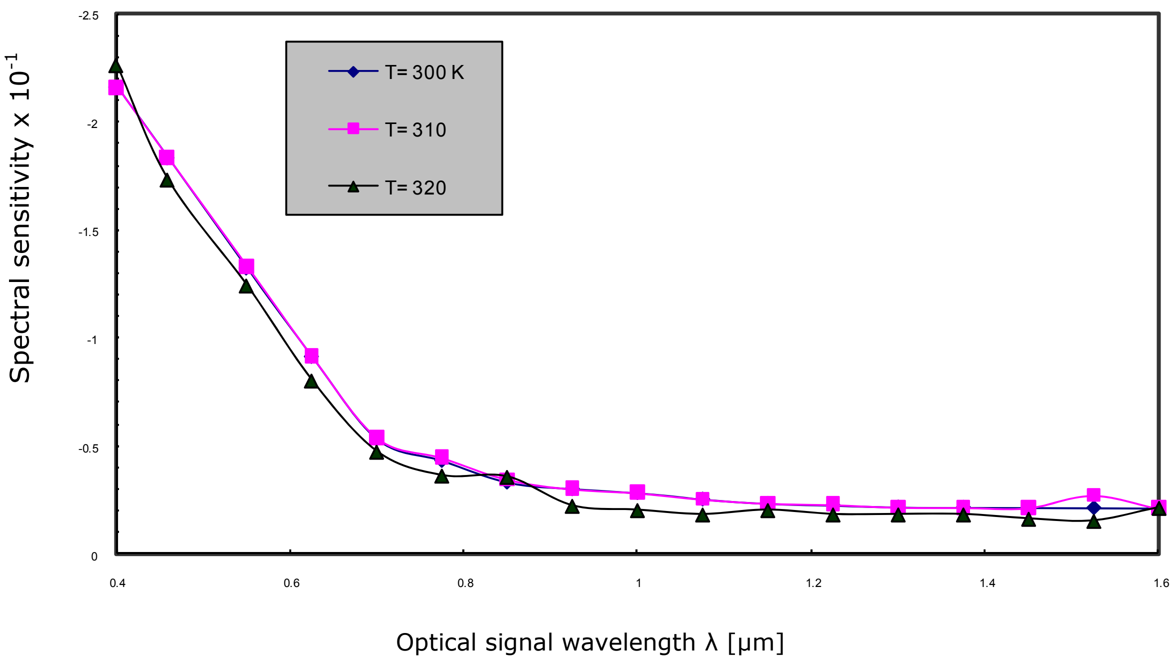


Figure 7. Variation of spectral sensitivity versus wavelength for $LiNbO_3$ material.

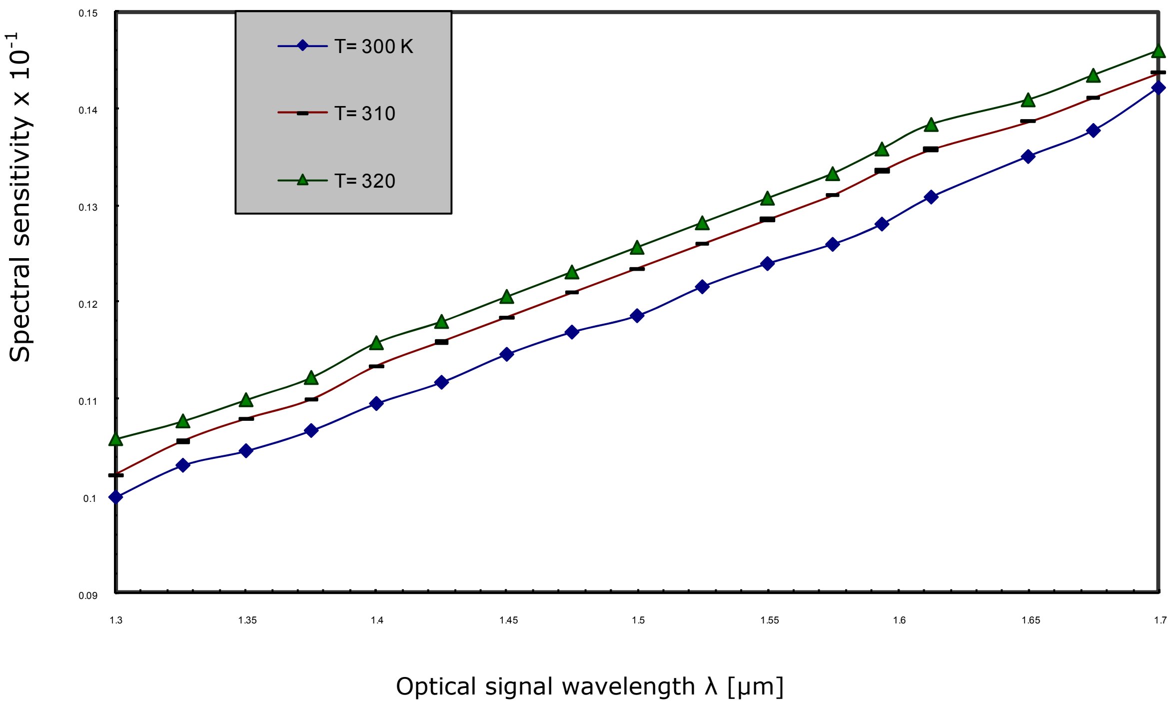


Figure 8. Variation of spectral sensitivity versus wavelength for Silica-doped material.

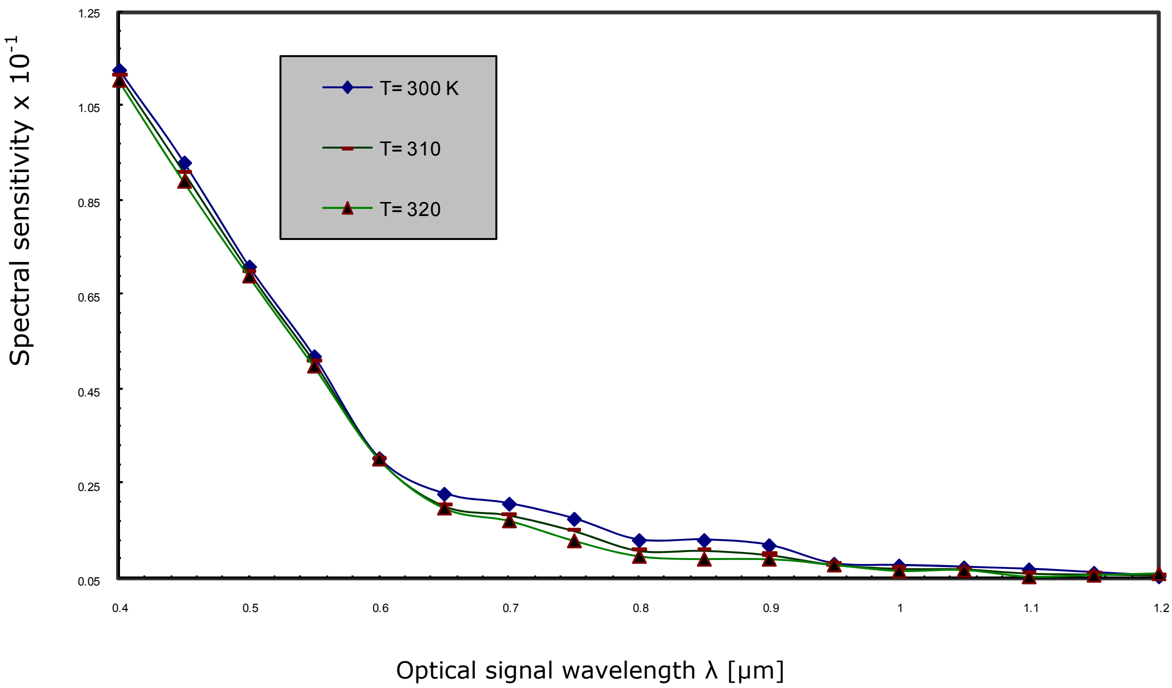


Figure 9. Variation of spectral sensitivity versus wavelength for PMMA material.

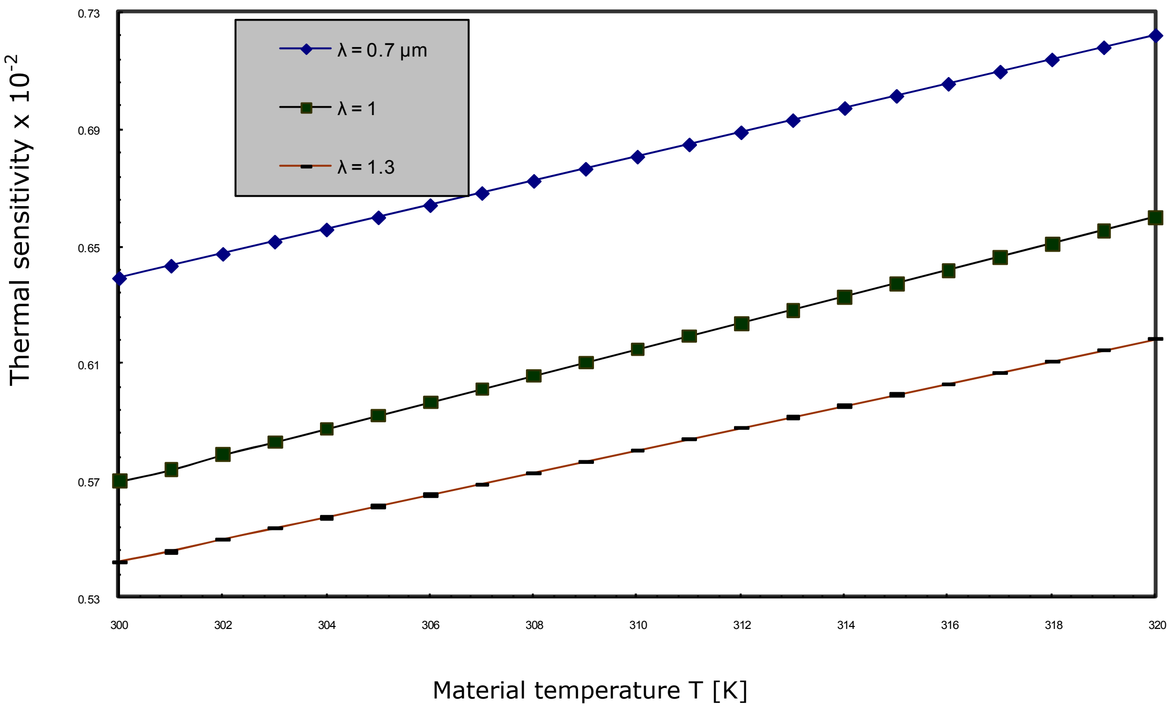


Figure 10. Variation of thermal sensitivity versus temperature for $LiNbO_3$ material.

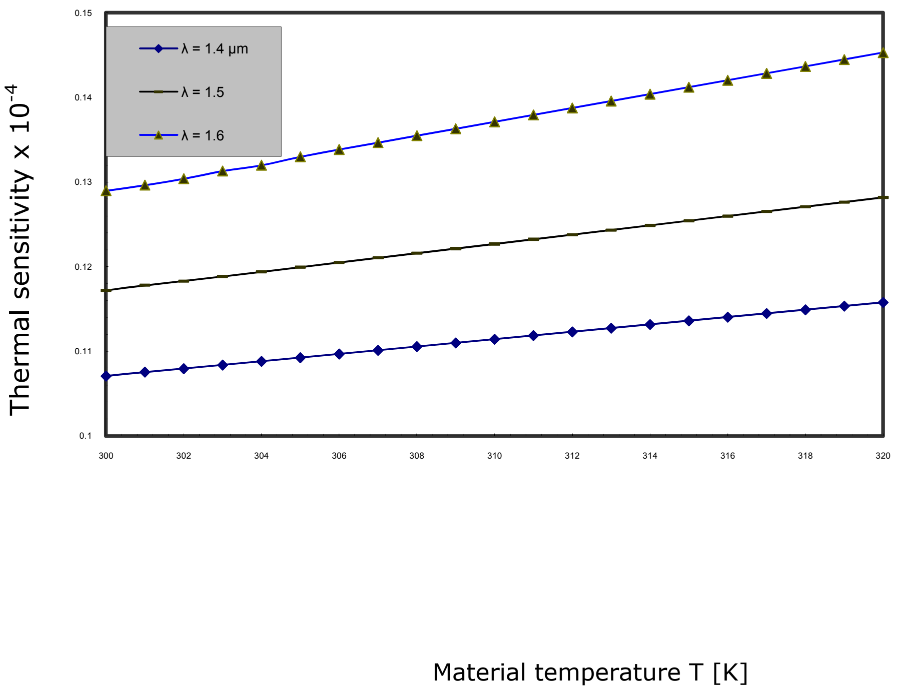


Figure 11. Variation of thermal sensitivity versus temperature for Silica-doped material.

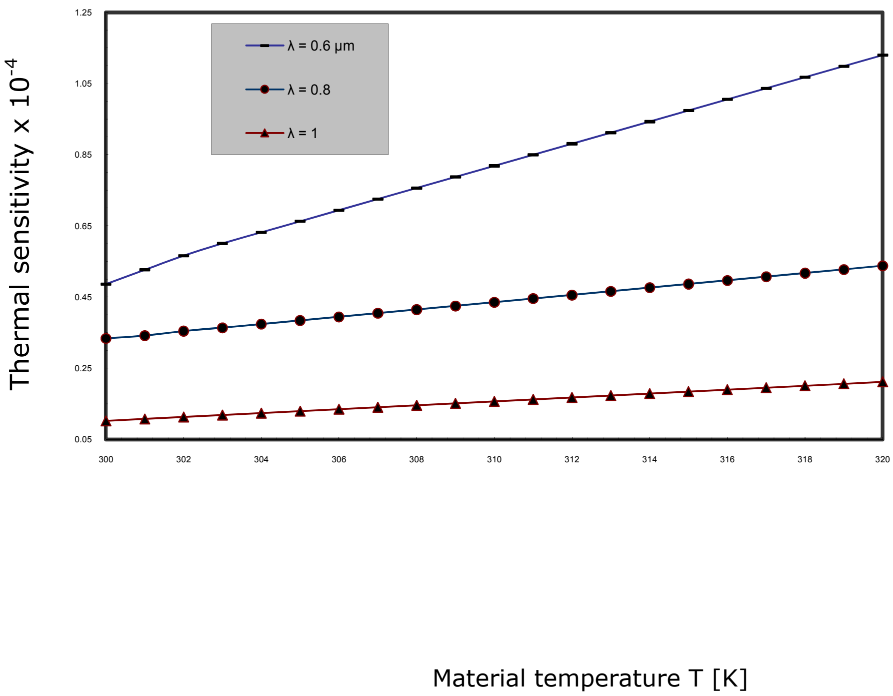


Figure 12. Variation of thermal sensitivity versus temperature for PMMA material.

2. 4. Sensitivities of waveguides

In fact, the thermal sensitivity S_T^n of n w. r. t T is defined as follows:

$$S_T^n = \left(\frac{T}{n}\right)\frac{dn}{dT} \tag{11}$$

And the spectral sensitivity S_λ^n of n w. r. t λ is defined as follows:

$$S_\lambda^n = \left(\frac{\lambda}{n}\right)\frac{dn}{d\lambda} \tag{12}$$

3. Results and Discussion

Thermal and spectral variations of n for the three waveguides are displayed in Figs. (1-6), these figures assure the following:

1- As the wavelength increases, (dn/dT or dn/dλ) of $LiNbO_3$ material decrease at constant T, and as the temperature increases, (dn/dT or dn/dλ) of $LiNbO_3$ material increase at constant λ. This indicates its thermal stability of $LiNbO_3$ material, dn/dT is constant at (T or λ).

2- As the wavelength increases, (dn/dT or dn/dλ) of Silica-doped material increase at constant T, and as the temperature increases, (dn/dT or dn/dλ) of Silica-doped material also increase at constant λ. This indicates its spectral stability of Silica-doped material, dn/dλ is constant at (T or λ).
3- As the wavelength increases, (dn/dT or dn/dλ) of PMMA Polymer material decrease at constant T, and as the temperature increases, (dn/dT or dn/dλ) of PMMA Polymer material also decrease at constant λ.

Thermal and spectral variations of S_T^n and S_λ^n for the three waveguides are also displayed in Figs. (7-12), the following features can be concluded:
4- As the wavelength increases, both the thermal and spectral sensitivities of $LiNbO_3$ material decrease at constant T, and as the temperature increases, the thermal sensitivity of $LiNbO_3$ material increase at constant λ.
5- As the wavelength increases, both the thermal and spectral sensitivities of Silica-doped material increase at constant T, and as the temperature increases, also both the thermal and spectral sensitivities of Silica-doped material increase at constant λ.
6- As the wavelength increases, both the thermal and spectral sensitivities of PMMA Polymer material decrease at constant T, and as the temperature increases, the thermal sensitivity of PMMA Polymer material increase at constant λ.

4. Conclusions

In a summary, three passive optical waveguides employed in PON and made of either Lithium niobate, Silica-doped fiber, and PMMA polymer fiber are spectrally and thermally investigated based on Sellmeier equation. Thermal and spectral sensitivities are also investigated. Positive correlations or negative correlations or both are found. In general, the three waveguides possess weak nonlinear correlations.

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Authors

Ahmed Nabih Zaki Rashed

was born in Menouf, Menoufia State, Egypt, in 1976. Received the B.Sc. and M.Sc. scientific degrees in the Electronics and Electrical Communication Engineering Department from Faculty of Electronic Engineering, Menoufia University in 1999 and 2005, respectively. Currently, his field interest and working toward the Ph.D degree in Active and Passive Optical Networks (PONs). His research mainly focuses on the transmission data rate and distances of optical access networks.