Applications of Conventional and A thermal Arrayed Waveguide Grating (AWG) Module in Active and Passive Optical Networks (PONs)

Abd El–Naser A. Mohammed and Ahmed Nabih Zaki Rashed

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.**

Index Terms—**Optical network, Arrayed waveguide gratings (AWGs), High integrated optics, planar waveguide, optical communications, Spectral and thermal sensitivities.**

I. INTRODUCTION

The explosive growth of Internet traffic is pushing the rapid development of high-speed broadband optical networks, such as dense wavelength-division multiplexing (DWDM) systems. In these optical networks, a variety of optical components such as wavelength-division multi/demultiplexers (MUX/DEMUXs), erbium-doped fiber amplifiers (EDFAs), lasers, photodetectors [2-4], and modulators are indispensable for constructing optical networks [1]. Among others, arrayed waveguide grating (AWG)-type MUX/DEMUXs based on the optical planers circuits (PLCs) have played an important role as a key optical component for DWDM. Meanwhile, in the midst of the telecom winter, many carriers are struggling to reduce per-bit cost. Therefore [5-7], optical components are expected to have new functions that reduce the operational and capital expenditures. For example, an AWG itself is expected to be athermal as well as low cost. In order to lower the cost of AWGs, besides testing and packaging costs, chip size is quite important because the number of AWGs laid out over a wafer determines the general cost. This is especially true for large-size optical circuits such as AWGs. The increase in refractive index difference between core and cladding is a quite useful way to reduce chip size. So far, several types of high-contrast waveguides have been reported to have been achieved by using several material systems, such as a semiconductor waveguide[8], SiON waveguide [9], Si-wire waveguides [10], and silica-based waveguide [11]. Among these waveguides, the silica-based waveguide is suitable in the light of low propagation loss as well as high reliability.

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The periodic and cyclic properties of AWGs are used to interconnect two adjacent ONUs by a piece of fiber. In the recent years, arrayed waveguide gratings (AWGs) have appeared to be one of attractive candidates for high channel count Mux/DeMux devices to process optical signals in a parallel manner. Its low chromatic dispersion, typically ±5 ps/nm — ±10 ps/nm, makes it possibly be used for 40 Gbit/s systems. However, it is well known that manufacturing AWGs involves a series of complex production processes and requires bulky facilities. Their cost remains a big issue. Further, the technical complexity leads to low yield and poor performance. The former, no doubt, further increases the production cost while the latter degrades the signal quality and system's performance, exhibiting high insertion loss, high channel crosstalk, low channel uniformity, and high polarization dependent loss. More vitally, AWGs require active temperature control in order to stabilize the thermal wavelength drift and temperature. Due to its capability to increase the aggregate transmission capacity of a single-strand optical fiber, the arrayed waveguide grating (AWG) multiplexer is considered a key component in the construction. material and PMMA cladding material is considered as the most attractive a thermal structure because of its resistance to the thermo-optic sensitivity of the materials. Arrayed Waveguide Gratings (AWGs) have increasingly become more important in Wavelength Division Multiplexing (WDM) systems. An AWG in silicon-on-insulator (SOI) is of particular interest because of both its technological andmaterial advantages [12]. The high index contrast in the SOI optical system results in a smaller device and better optical confinement within the waveguide as compared to low index contrast systems [13]. Also, the mature microelectronic fabrication technology can be easily transferred to most of the SOI photonic devices. The spectral response of a typical SOI AWG exhibits a Gaussian profile, which restricts the wavelength selectivity of the devices due to wavelength drift caused by the laser diode and the AWG. Therefore [14], a flat spectral response is desirable to ease the wavelength selectivity of the WDM system. Various methods have been proposed and demonstrated in different material systems and each has its own advantages and disadvantages [15]. To date, with the explosive growth of end user demand for higher bandwidth, various types of passive optical networks (PONs) have been proposed. PON can be roughly divided into two categories such as time-division-multiplexing (TDM) and wavelength-division-multiplexing (WDM) methods [16]. Compared with TDM-PONs, WDM-PON systems allocate a separate wavelength to each subscriber, enabling the delivery of dedicated bandwidth per optical network unit (ONU). Moreover, this virtual point-to-point connection enables a large guaranteed bandwidth, protocol transparency, high quality of service, excellent security, bit-rate independence, and easy upgradeability. Especially, recent good progress on athermal arrayed waveguide grating (AWG) and cost-effective colorless ONUs [17] has empowered WDM-PON as an optimum solution for the modern optical access telecommunication networks.

Arrayed waveguide grating (AWG) which handles the function of wavelength multiplexer/demultiplexer is extensively used in configuring optical communication networks that are becoming more diversified. Since the transmission wavelength of an AWG is temperature dependent, it was a common practice to control its temperature using heaters or Peltier elements. But this caused problems of power consumption increase in the whole system in addition to limiting the installation locations of AWGs, thus making it difficult to respond to various needs of the next-generation optical communication networks, despite the fact that system performance upgrading and function enhancement are required in recent years. However, fiber link failure from the optical line terminal (OLT) to the ONU leads to the enormous loss of data. Thus, fault monitoring [18] and network protection [19] are crucial issues in network operators for reliable network. To date, many methods have been proposed for network protection. In the ITU-T recommendation on PONs (G.983.1), duplicated network resources such as fiber links or ONUs are required. Planar light-wave circuit technology and design have evolved significantly in the past decade, in terms of both performance and yield. New semiconductor techniques applied to integrated optics have dramatically improved wafer quality; in parallel, design efforts have led to lowering insertion loss, reducing crosstalk, increasing channel bandwidth, decreasing channel spacing, and managing chromatic dispersion (CD). With arrayed waveguide gratings (AWGs) that match or exceed the performance of thin-film filters, and will enable with the integration of variable optical attenuators and monitoring taps to realize high-performance and low-cost modules with added functions for the system. Desirable characteristics of any AWG device include low loss in the passbands, high loss outside the passbands, uniform loss within one channel and channel-to-channel, and polarization-independent behavior. While low crosstalk is of paramount importance in demultiplexers where out-of-band signals appear as noise at the receiver, it is of little concern in multiplexers where out-of-band signals simply are not present in the transmitter. For multiplexing, a flat response within the passband is highly desirable in order to account for wavelength drift in the laser source. The explosion in demand for Internet services is promoting the rapid development of high-speed and broad-and optical networks such as fiber to the home (FTTH) and dense wavelength division multiplexing (DWDM) systems. Such networks require a variety of optical components including micro optics, fiber, and planar-type elements. Planar light wave circuits (PLC) fabricated using silica-based waveguides are employed in various devices because of their excellent design flexibility, stability, and mass-reducibility. Of the PLC-type devices, arrayed waveguide gratings (AWGs) are superior to other types of wavelength multi/demultiplexers, such as dielectric multilayered filters, in terms of compactness and multichanneling. Today, optical networks are required to be more broad-band and economical. Therefore, it is hoped that DWDM systems will increase their capacity and spread throughout the access networks. At the same time, there is also a need for AWG multi/demultiplexers to be further improved in terms of channel count and made more compact and less expensive. Moreover, the functionsand scale of PLCs should be enhanced to allow us to construct future photonic networks that need advanced optical processing such as optical switching and routing. To meet these requirements, it is important that we improve PLCs in terms of low-loss and high-density integration [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).

II. SYSTEM MODEL ANALYSIS

A. LITHIUM NIOBATE (LiNbO3) 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]:

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

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:

$$n^2 = A_{12} + \frac{A_{34}}{l^2 - A_{56}^2} + \frac{A_{78}}{l^2 - A_9^2} - A_{10} l^2 \quad (2)$$

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:

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

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

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

B. GERMANIA DOPED SILICA (GeO2(x)+SiO2(1-x)) MATERIAL

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

$$n^2=1+\frac{B_1 l^2}{l^2-B_2^2}+\frac{B_3 l^2}{l^2-B_4^2}+\frac{B_5 l^2}{l^2-B_6^2} \quad (5)$$

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:

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

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

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

C. POLYMETHYL-METHA ACRYLATE (PMMA) POLYMER MATERIAL

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

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

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:

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

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

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

D. SENSITIVITIES OF WAVEGUIDES

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

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

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

$$S_l^n=\left(\frac{l}{n}\right)\frac{dn}{dl} \quad (12)$$

III. RESULTS AND DISCUSSIONS

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

1- (dn/dT or dn/dλ) against the variations of (T or λ) at constant (λ or T) possesses either positive or negative correlations for three optical waveguides.

2- 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).

3- 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).

4- 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_l^n for the three waveguides are also displayed in Figs. (7-12), the following features can be concluded:

5 As the wavelength increases, both the thermal and spectral sensitivities of LiNbO3 material decrease at constant T, and as the temperature increases, the thermal sensitivity of LiNbO3 material increase at constant λ.

6- 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.

7- As the wavelength increases, both the thermal and spectral sensitivities of PMMA Polymer material7- 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.

IV. 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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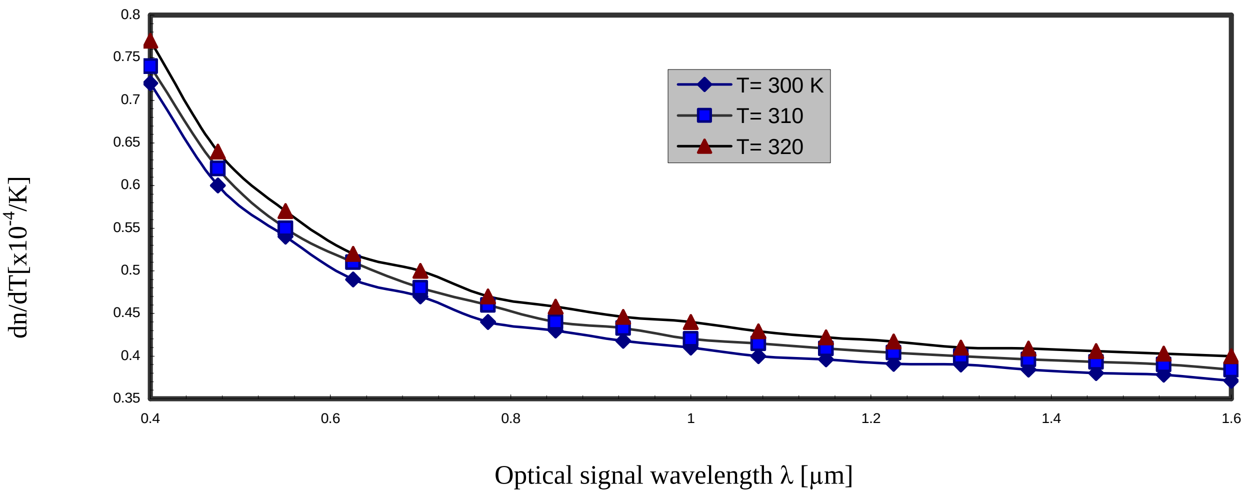

Fig. 1. Variation of dn/dT versus wavelength for $LiNbO_3$ material

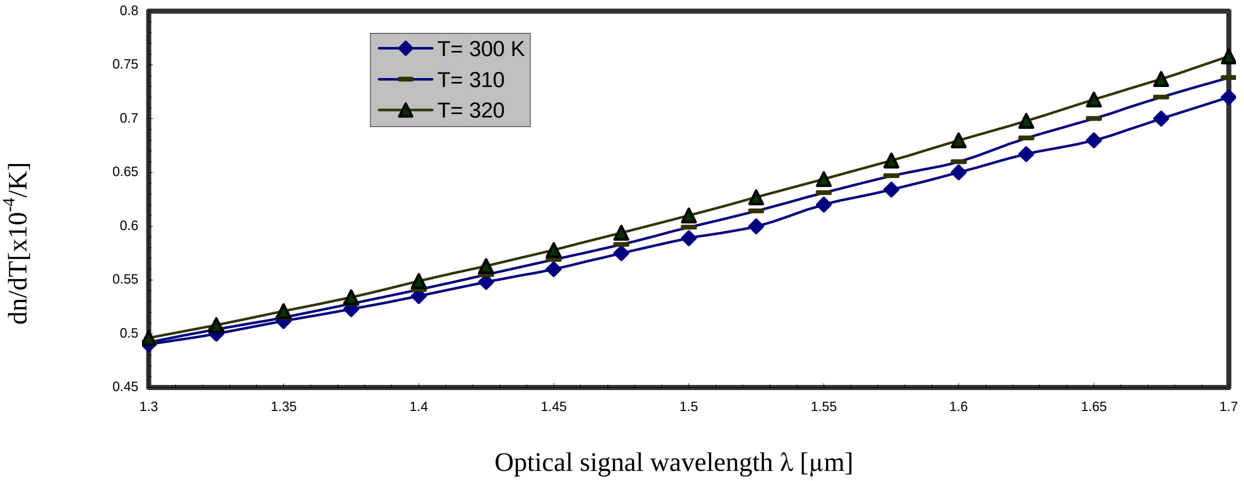

Fig. 2. Variation of dn/dT versus wavelength for Silica- doped material

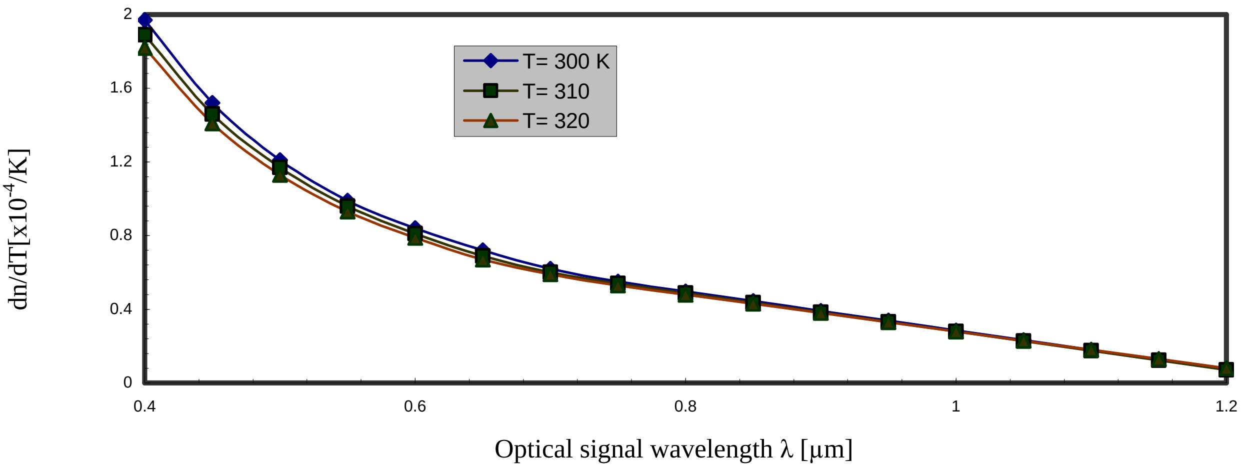

Fig. 3. Variation of dn/dT versus wavelength for PMMA material

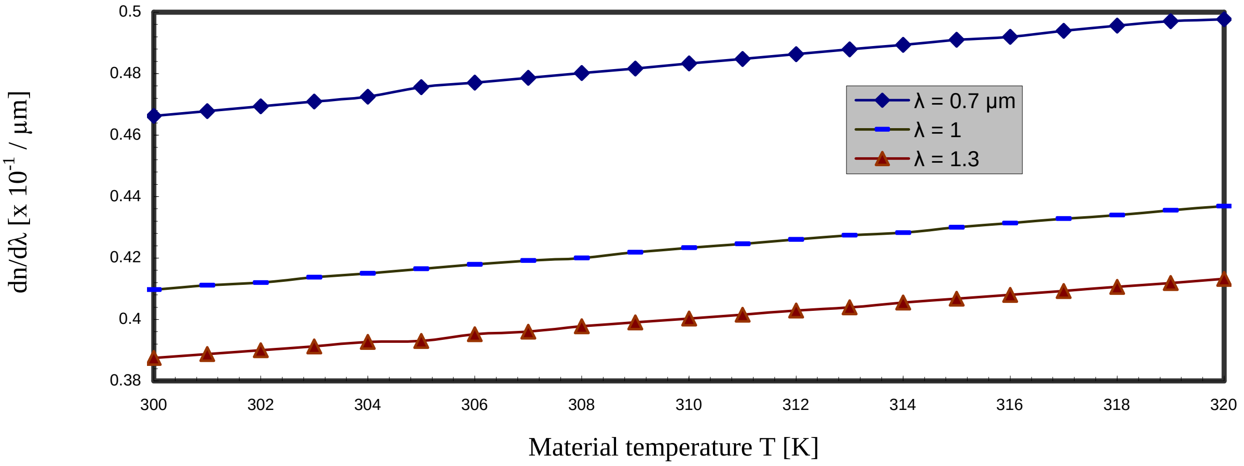

Fig. 4. Variation of dn/dλ versus temperature for $LiNbO_3$ material

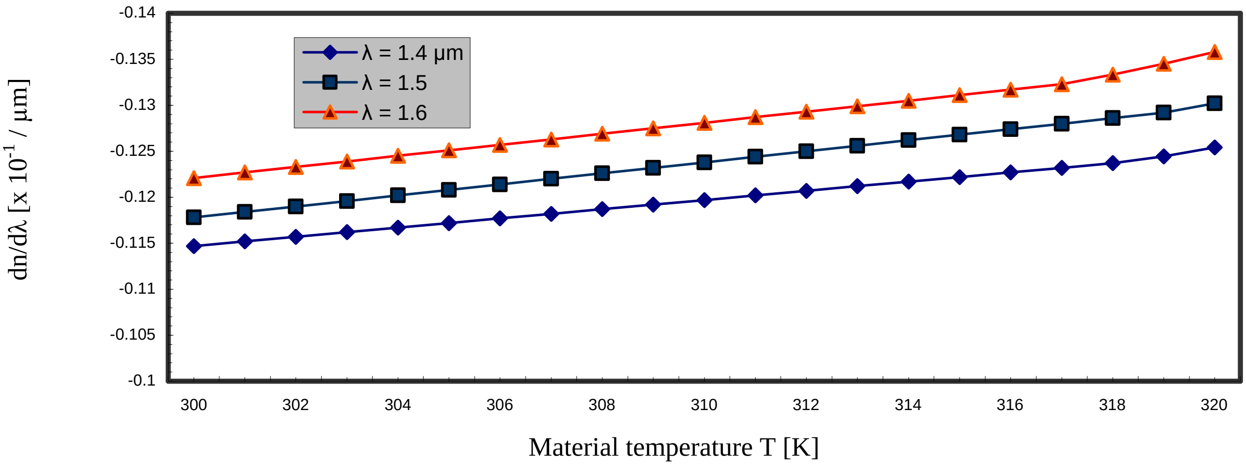

Fig. 5. Variation of dn/dλ versus temperature for Silica-doped material

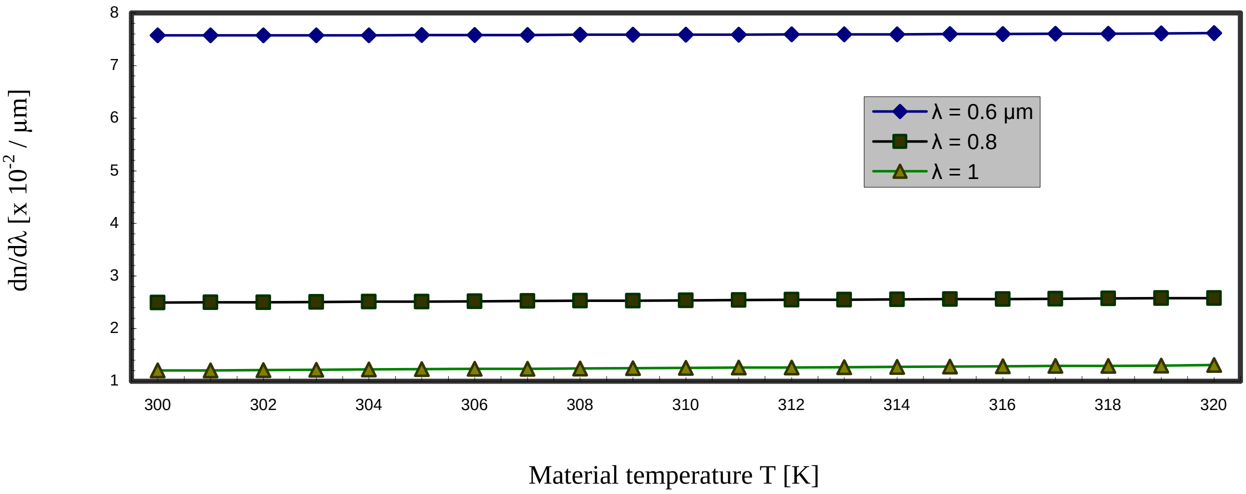

Fig. 6. Variation of dn/dλ versus temperature for PMMA material

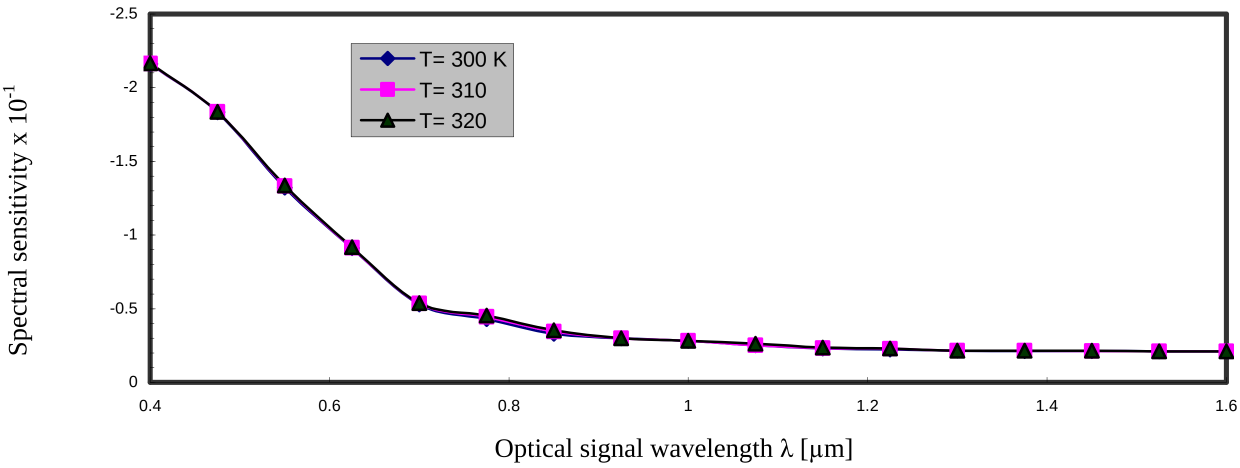

Fig. 7. Variation of spectral sensitivity versus wavelength for $LiNbO_3$ material

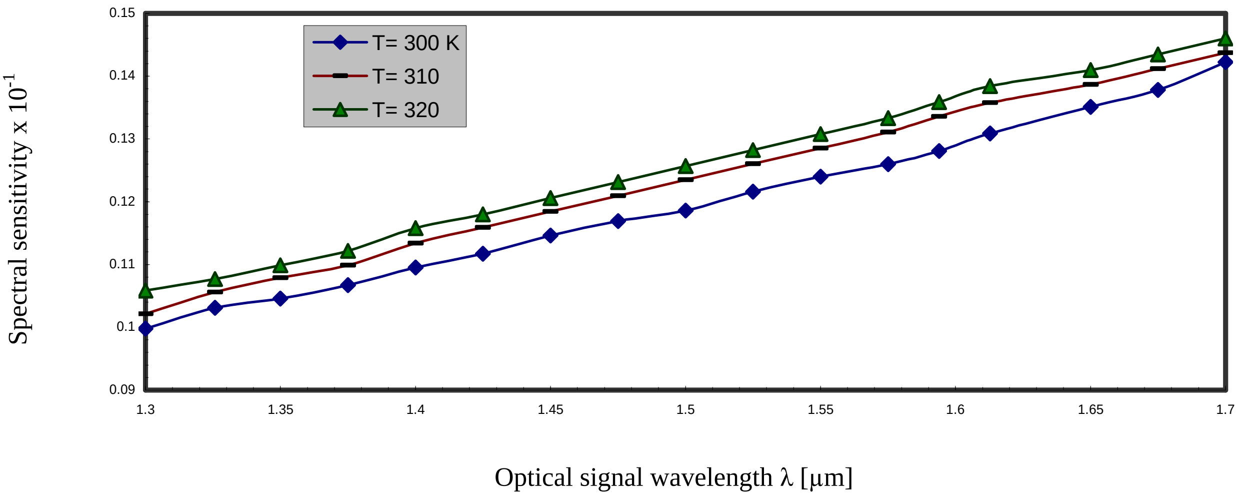

Fig. 8. Variation of spectral sensitivity versus wavelength for Silica-doped material

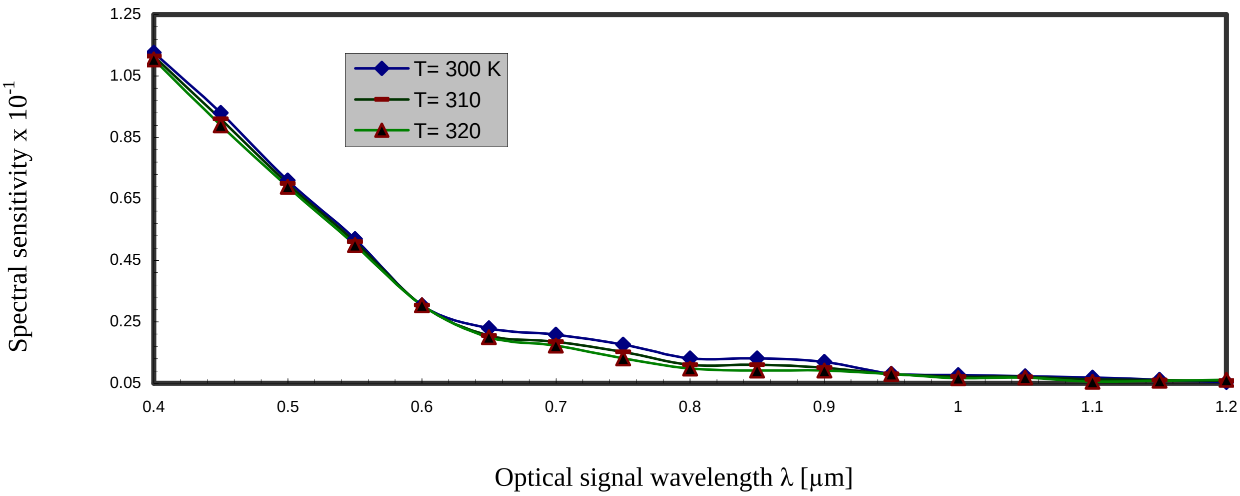

Fig. 9. Variation of spectral sensitivity versus wavelength for PMMA materia

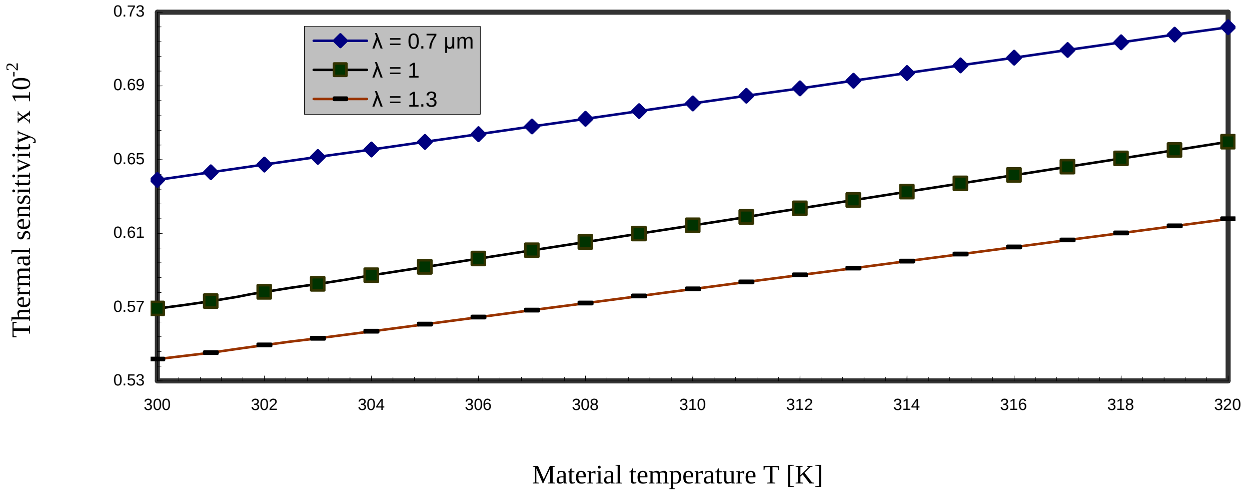

Fig. 10. Variation of thermal sensitivity versus temperature for $LiNbO_3$ material

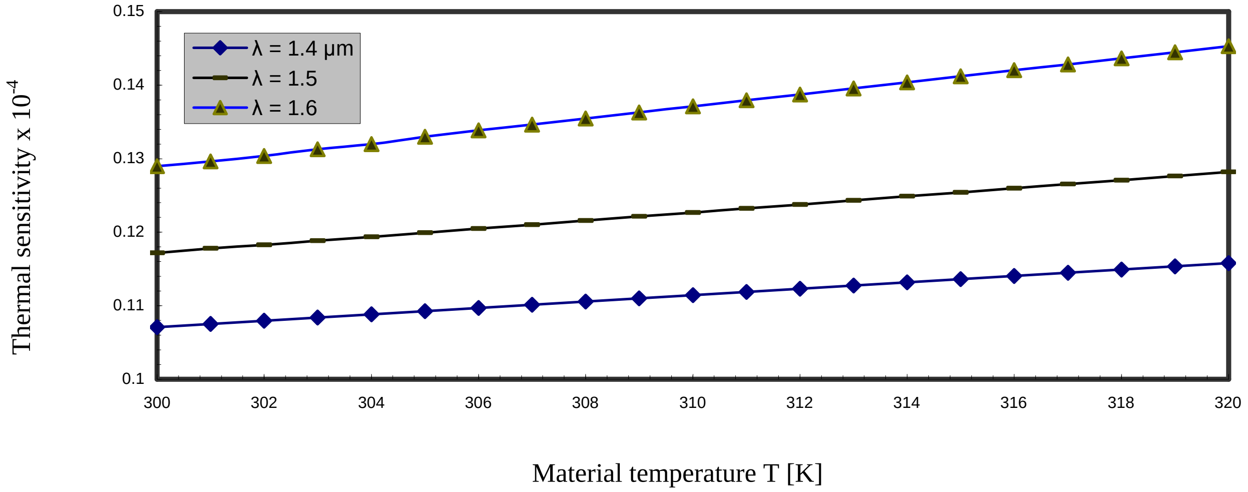

Fig. 11. Variation of thermal sensitivity versus temperature for Silica-doped material

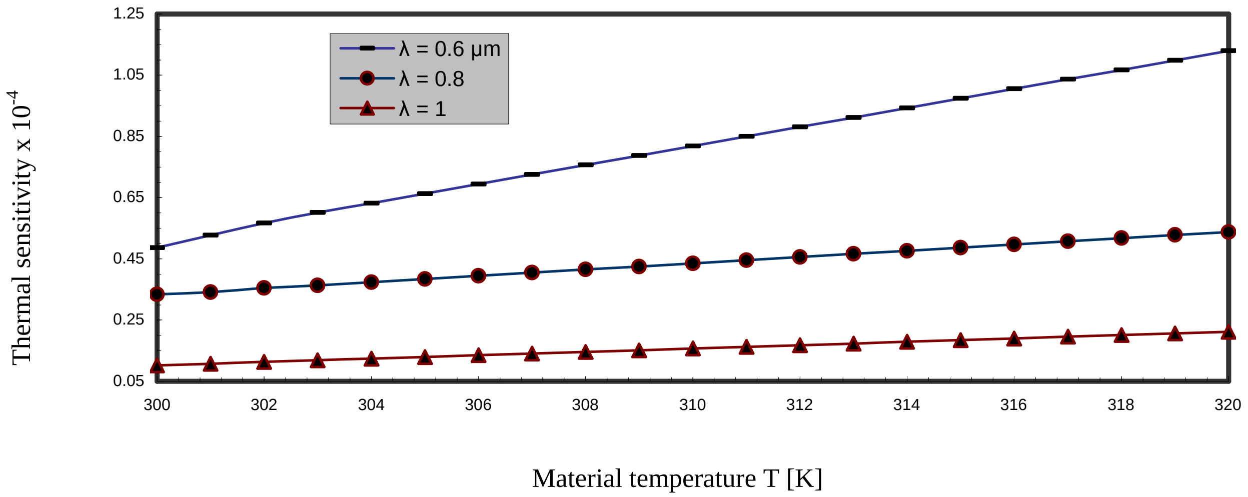

Fig. 12. Variation of thermal sensitivity versus temperature for PMMA material