

Characteristics of the fabrication materials based Arrayed Waveguide grating (AWG) in Passive Optical Networks (PONs)

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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 methacrylate (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: Arrayed Waveguide Grating (AWG), Lithium Niobate (LiNbO_3) material, Silica-doped material, Polymethyl-methacrylate (PMMA) Polymer material.

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) systems¹. In these optical networks, a variety of optical components such as wavelength-division multi/demultiplexers (MUX/DEMUXs), erbium-doped fiber amplifiers (EDFAs), lasers, photodetectors²⁻⁴, and modulators are indispensable for constructing optical networks. Among others, arrayed waveguide grating (AWG)-type MUX/DEMUXs based on planar lightwave 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. Therefore⁵⁻⁷, 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 waveguide⁸, SiON waveguide⁹, Si-wire waveguides¹⁰, and silica-based waveguide¹¹. Among these waveguides, the silica-based waveguide is suitable in the light of low propagation loss as well as high reliability.

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 and material advantages¹². 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 systems¹³. 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. Therefore¹⁴, 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 disadvantages¹⁵. 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) methods¹⁶. 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 ONUs¹⁷ has empowered WDM-PON as an optimum solution for the access network. However, fiber link failure from the optical line terminal (OLT) to the ONU leads to the enormous loss of data. Thus, fault monitoring¹⁸ and network protection¹⁹ 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 required²⁰.

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).

Theoretical model and equations analysis

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.:

$$n^2 = A_1 + A_2H + \frac{A_3 + A_4H}{\lambda^2 - (A_5 + A_6H)^2} + \frac{A_7 + A_8H}{\lambda^2 - A_9^2} - A_{10}\lambda^2 \quad \dots(1)$$

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 (LiNbO₃) are recast and dimensionally adjusted as below 21.: $A_1=5.35583$, $A_2=4.629 \times 10^{-7}$, $A_3=0.100473$, $A_4=3.862 \times 10^{-8}$, $A_5=0.20692$, $A_6=-0.89 \times 10^{-8}$, $A_7=100$, $A_8=2.657 \times 10^{-5}$, $A_9=11.34927$, and $A_{10}=0.01533$. Equation (1) can be simplified as:

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

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:

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

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

$$\frac{dn}{dT} = \left(\frac{T}{n}\right) \left[A_1 + \frac{(\lambda^2 - A_2^2) A_2 + 2A_3 A_2 A_4}{(\lambda^2 - A_2^2)^2} + \frac{A_4}{(\lambda^2 - A_4^2)} \right] \dots (4)$$

Germania doped silica (GeO₂(x)+SiO₂(1-x)) material

The refractive index of this waveguide is cast as 22.:

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

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

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

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

$$\frac{dn}{d\lambda} = -(\lambda/n) \left[\frac{B_1 B_2}{(\lambda^2 - B_2^2)^2} + \frac{B_3 B_4}{(\lambda^2 - B_4^2)^2} + \frac{B_5 B_6}{(\lambda^2 - B_6^2)^2} \right] \dots (6)$$

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

$$\frac{dn}{dT} = \left(-\lambda/n\right) \left[\frac{B_1 B_2 \frac{\partial B_2}{\partial T}}{(\lambda^2 - B_2^2)^2} + \frac{B_3 B_4 \frac{\partial B_4}{\partial T}}{(\lambda^2 - B_4^2)^2} + \frac{B_5 B_6 \frac{\partial B_6}{\partial T}}{(\lambda^2 - B_6^2)^2} \right] \dots (7)$$

Polymethyl-metha acrylate (PMMA) polymer material

The refractive index of this waveguide is cast as 23.:

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

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:

$$\frac{dn}{d\lambda} = -(\lambda/n) \left[\frac{C_1 C_2^2}{(\lambda^2 - C_2^2)^2} + \frac{C_3 C_4^2}{(\lambda^2 - C_4^2)^2} + \frac{C_5 C_6^2}{(\lambda^2 - C_6^2)^2} \right] \dots (9)$$

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

$$\frac{dn}{dT} = \left(-\lambda/n\right) \left[\frac{C_1 C_2 \frac{\partial C_2}{\partial T}}{(\lambda^2 - C_2^2)^2} + \frac{C_3 C_4 \frac{\partial C_4}{\partial T}}{(\lambda^2 - C_4^2)^2} + \frac{C_5 C_6 \frac{\partial C_6}{\partial T}}{(\lambda^2 - C_6^2)^2} \right] \dots (10)$$

Sensitivities of waveguides

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

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

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

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

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. $(dn/dT \text{ or } dn/d\lambda)$ 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, $(dn/dT \text{ or } dn/d\lambda)$ of LiNbO₃ material decrease at constant T, and as the temperature increases, $(dn/dT \text{ or } dn/d\lambda)$ of LiNbO₃ material increase at constant λ . This indicates its thermal stability of LiNbO₃ material, dn/dT is constant at (T or λ).
3. As the wavelength increases, $(dn/dT \text{ or } dn/d\lambda)$ of Silica-doped material increase at constant T, and as the temperature

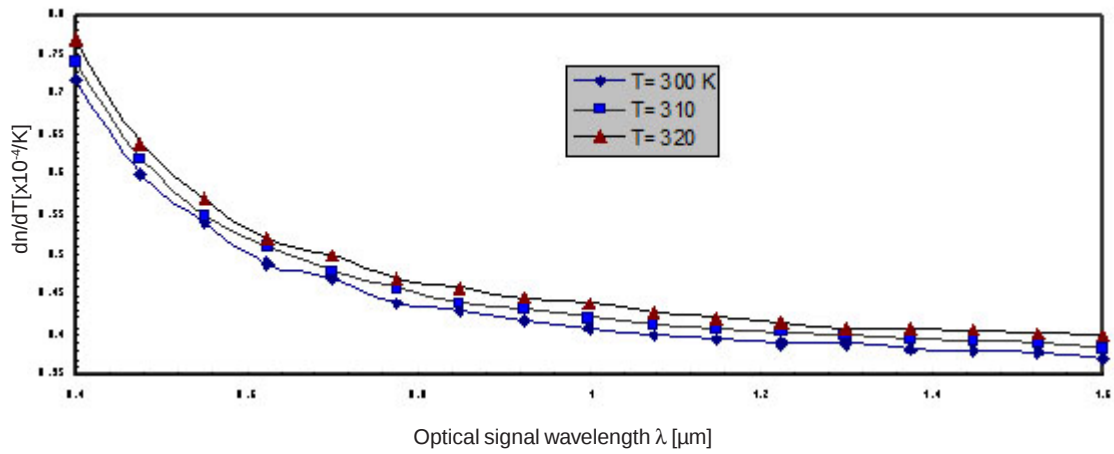


Fig. 1: Variation of dn/dT versus wavelength for LiNbO_3 material

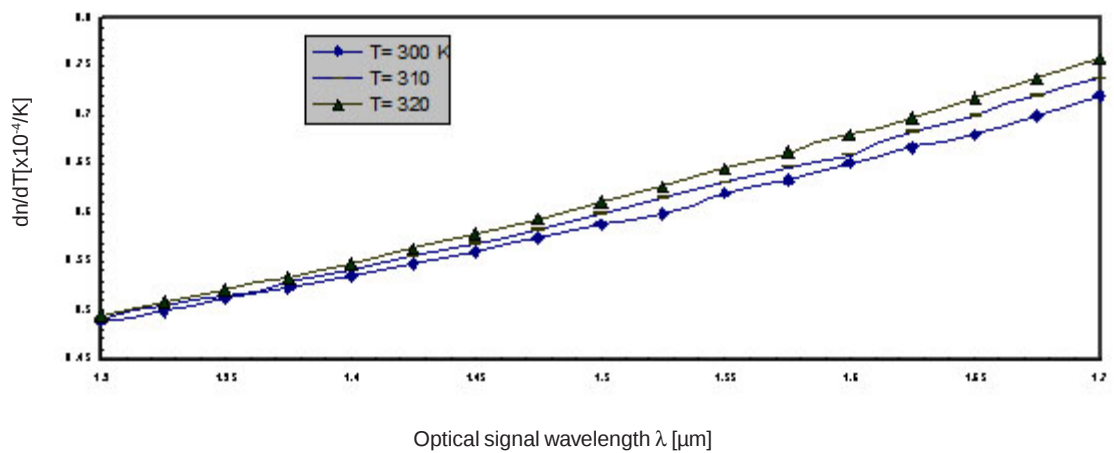


Fig. 2: Variation of dn/dT versus wavelength for Silica-doped material

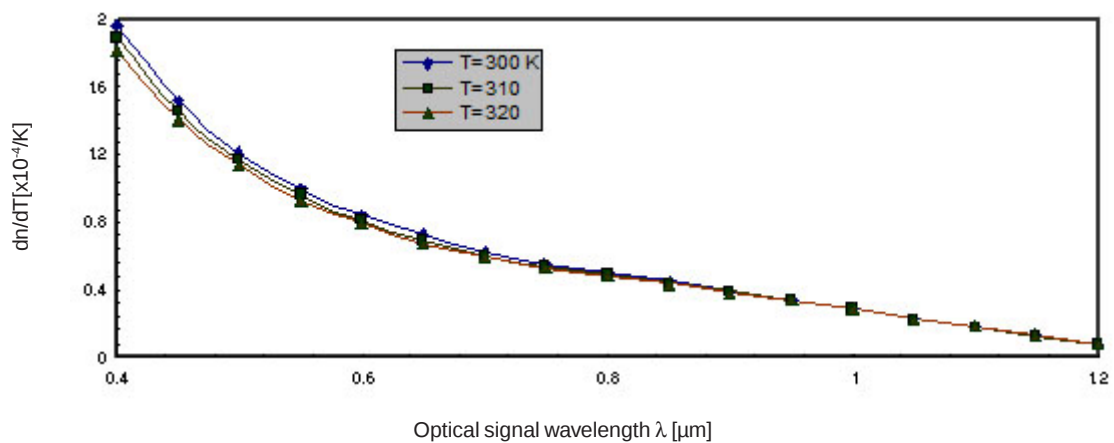


Fig. 3: Variation of dn/dT versus wavelength for PMMA material

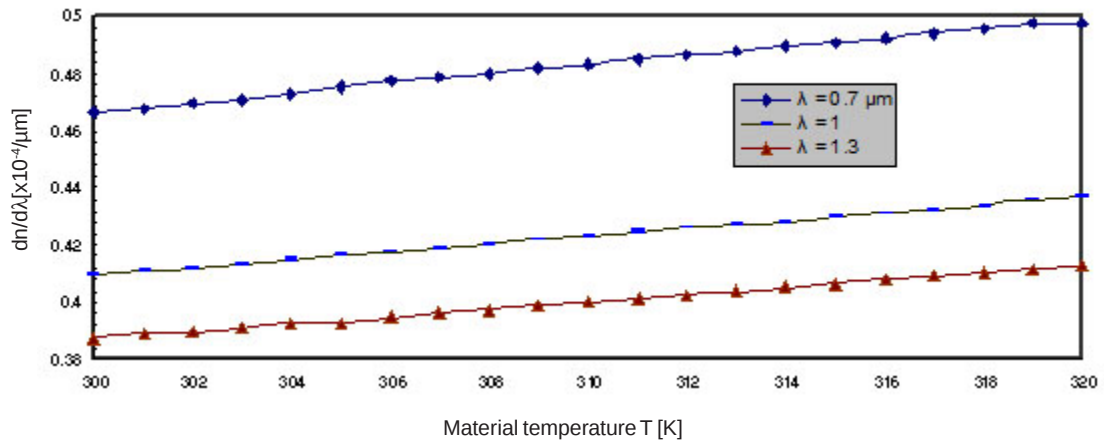


Fig. 4: Variation of $dn/d\lambda$ versus temperature for LiNbO_3 material

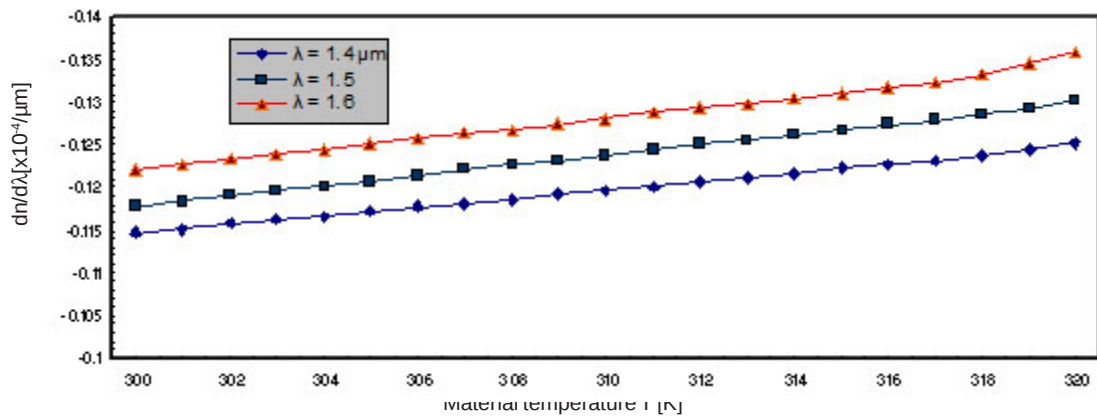


Fig. 5: Variation of $dn/d\lambda$ versus temperature for Silica-doped material

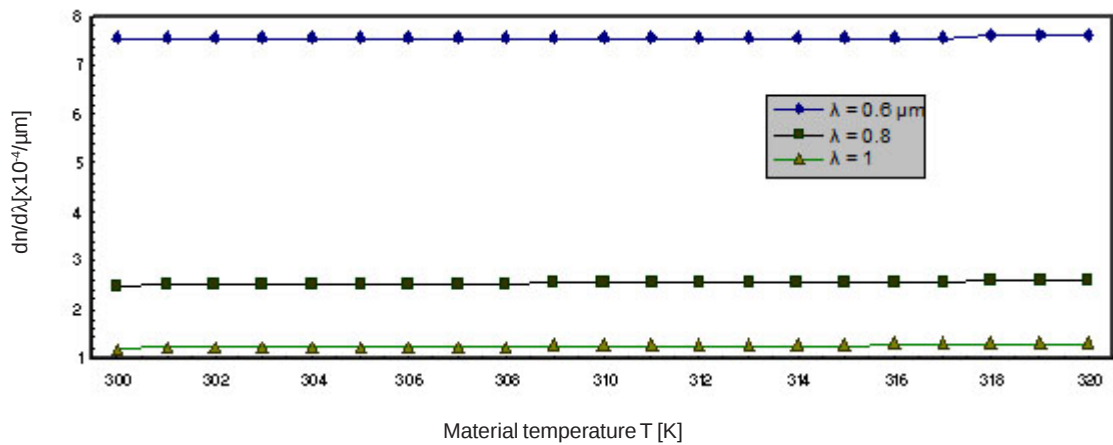


Fig. 6: Variation of $dn/d\lambda$ versus temperature for PMMA material

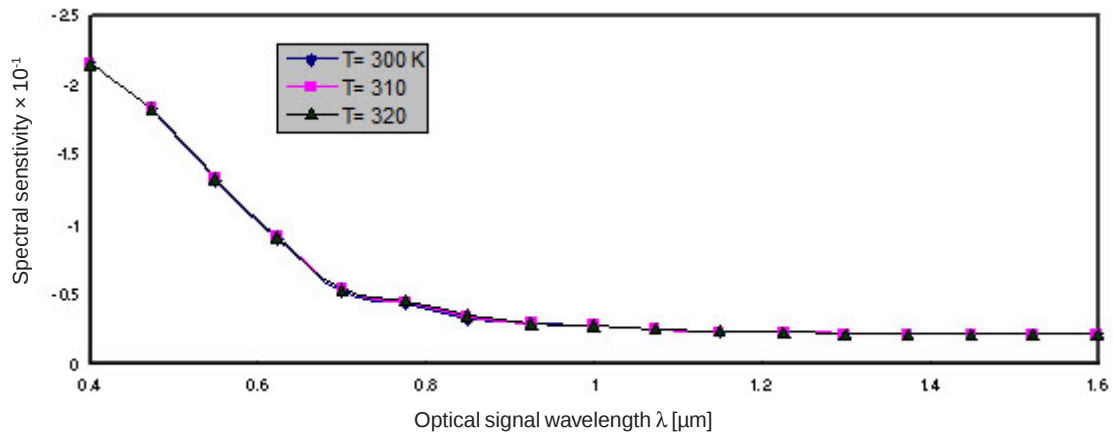


Fig. 7: Variation of spectral sensitivity versus wavelength for LiNbO_3 material

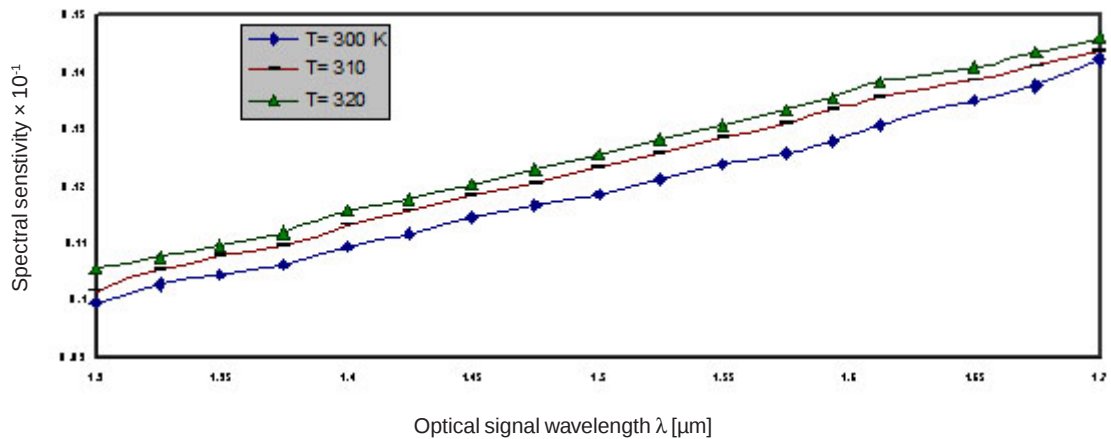


Fig. 8: Variation of spectral sensitivity versus wavelength for Silica-doped material

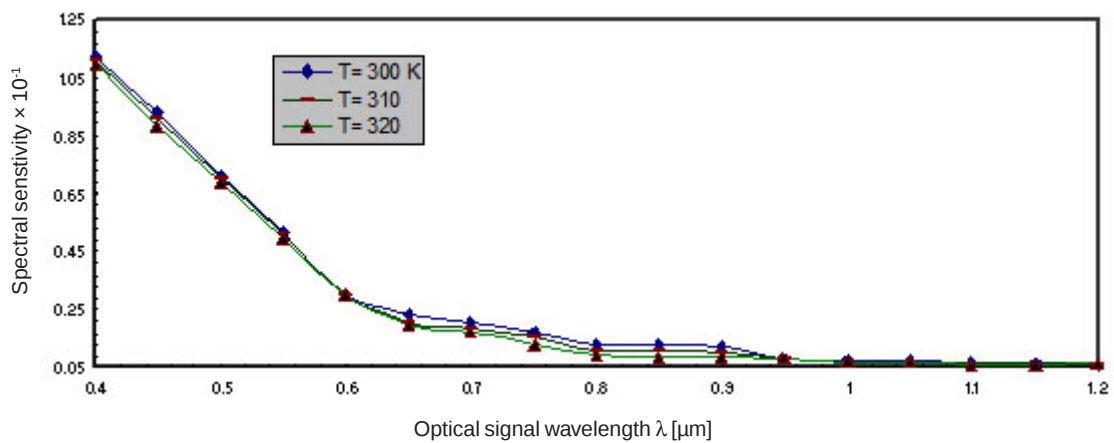


Fig. 9: Variation of spectral sensitivity versus wavelength for PMMA material

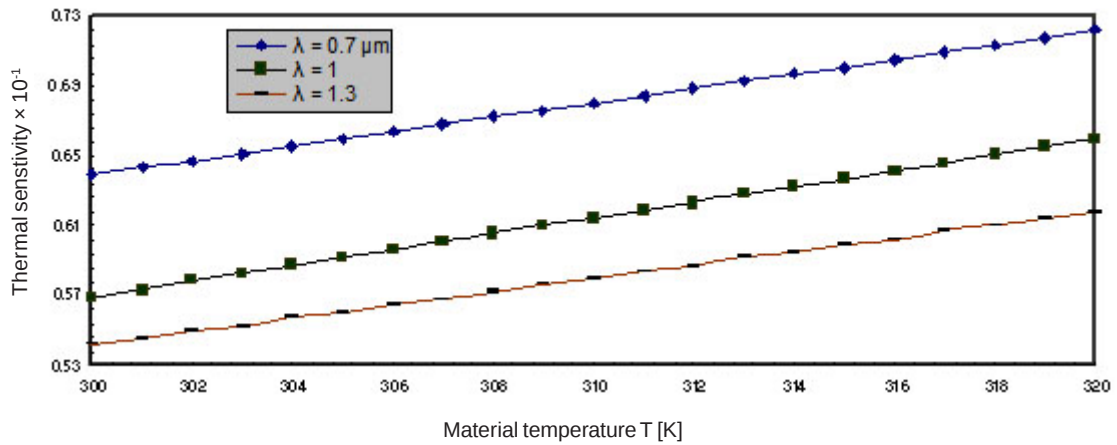


Fig. 10: Variation of thermal sensitivity versus temperature for LiNbO₃ material

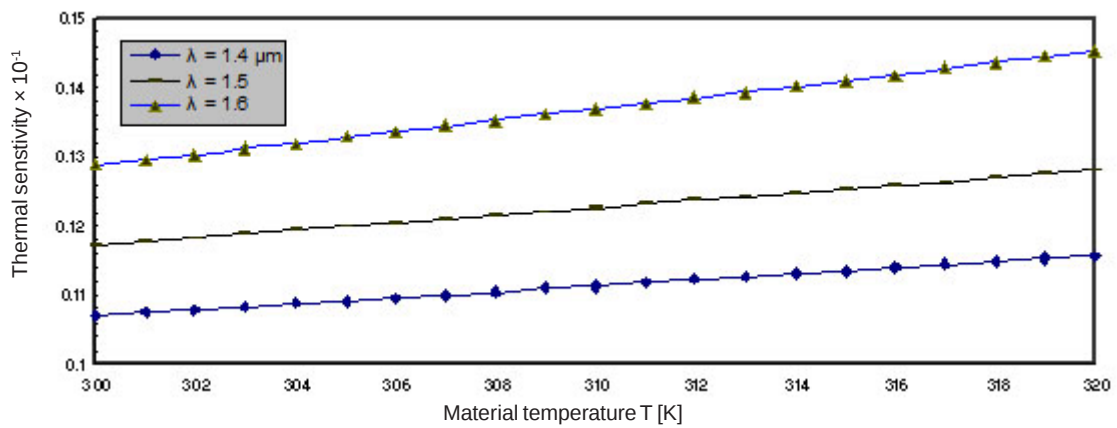


Fig. 11: Variation of thermal sensitivity versus temperature for Silica-doped material

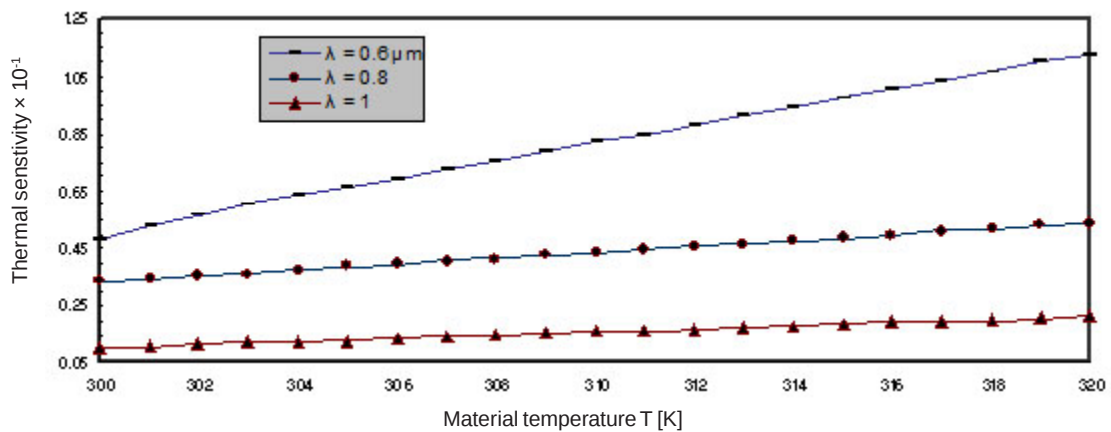


Fig. 12: Variation of thermal sensitivity versus temperature for PMMA material

increases, $(dn/dT \text{ or } dn/d\lambda)$ of Silica-doped material also increase at constant λ . This indicates its spectral stability of Silica-doped material, $dn/d\lambda$ is constant at $(T \text{ or } \lambda)$.

4. As the wavelength increases, $(dn/dT \text{ or } dn/d\lambda)$ of PMMA Polymer material decrease at constant T , and as the temperature increases, $(dn/dT \text{ or } dn/d\lambda)$ 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:

1. 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 .
2. 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 .

3. 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 .

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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