International Journal of Communication Networks and Information Security (IJCNIS) Vol. 1, No. 2, August 2009

Low Loss a thermal Arrayed Waveguide Grating (AWG) Module for Passive and Active Optical Network Applications

Abd El–Naser A. Mohammed[1], Ahmed Nabih Zaki Rashed[2*],
Gaber E. S. M. El-Abyad[3], Abd El–Fattah A. Saad[4]

[1,2,3,4]Electronics and Electrical Communication Engineering Department
Faculty of Electronic Engineering, Menouf 32951, Menoufia University, EGYPT
[1]E-mail: abd_elnaser6@yahoo.com, [2*]E-mail: ahmed_733@yahoo.com

Abstract: In the present paper, we have investigated parametrically and numerically the low loss a thermal arrayed waveguide grating (AWG) which is composed of lithium niobate ($LiNbO_3$)/polymer/silica-doped hybrid materials on a silicon substrate module for Passive and active optical Network applications. The modeling has parametrically analyzed and investigated over wide range of the affecting parameters. Also, we have theoretically investigated the temperature dependent wavelength shift of the arrayed waveguide grating (AWG) depends on the refractive-indices of the materials and the size of the waveguide. A thermalization of the AWG can be realized by selecting proper values of the material and structural parameters of the device.

Key words: Active optical network, Passive optical network A thermal Arrayed waveguide gratings (AWGs), Fiber optics, optical slab waveguide, Access networks, Thermo-optic effect, Hybrid materials.

1. Introduction

Wavelength division multiplexing (WDM) optical networks are currently implemented in most wide area networks (WAN) and metropolitan area networks (MAN) and their implementation in access networks is growing rapidly. This is mainly motivated by the rapid increase in the bandwidth required by the subscriber, especially with the massive use of the internet and online computing [1]. While dense WDM (DWDM) is adopted for the WAN and MAN networks, access networks are more sensitive to cost and thus the use of the coarse WDM (CWDM) technique could be more suitable for such applications due to the large channel separations which eliminates the need for high cost, well-stabilized laser sources required in DWDM systems. The design of (DE)MUXs compatible with the CWDM standard is a challenging task due to the tight restrictions on the required response. Thin film filters (TFF) are currently used for this application [2]. However, they should be used either with splitters, which increases the system insertion loss, or in a cascade configuration, which degrades the DEMUX uniformity. A more suitable solution, especially for large numbers of channels, would be the use of a planar light wave circuit (PLC) to achieve the One of the strongest candidates in PLCs is the arrayed waveguide grating (AWG) that has already demonstrated its value in DWDM applications. However, AWG is more compatible with DWDM narrow channel separations (1 nm or lower), and very few designs have been proposed for CWDM applications [3]. Actually, a conventional AWG is characterized by a Gaussian-like response in its pass band. This response is suitable for DWDM systems where the channel spacing is very small, of the order of 1 nm, and the source wavelength is so stable that the signal only sees the peak of the response. In CWDM, the channel spacing is 20 nm and the pass band, according to the ITU G.694.2, is 13 nm to accommodate the wavelength drift of an uncooled laser source. In wavelength division multiplexing (WDM) systems with large number of channels, there is the need of inserting a large number of channels in a single optical fiber. For this purpose [4], several devices have been developed, and the arrayed-waveguide grating (AWG) has been indicated as a proper choice. This is due to the properties of such a device and to the simplicity of manufactory. However, there are limitations in the use of AWG devices in dense WDM (DWDM) systems [5]. One of these limitations is related to the value of free spectral range (FSR), which reduces the number of channels multiplexed or demultiplexed. Other limitation is related with the small isolation between channels that this kind of device can provide [6]. Taking this into account, it is desirable to have a method of determining the AWG physical dimensions that lead to the channel spacing and full width half maximum (FWHM) required for all the channels of the DWDM system. With the increasing diversity of D-WDM systems in recent years, one of the needs facing the AWG, which handles the function of wavelength multiplexer/demultiplexer, is for a thermalization (temperature-independence) requiring no power supply. The advantages of a thermalization are, most obviously, elimination of the need for a power supply [7], plus the fact that there is no need to monitor the temperature of the AWG module. This would make it possible for the AWG module to be isolated from transmission devices inside an office and to be installed in a variety of locations having no power supply, making them able to satisfy the needs of the increasingly diversified optical communications networks of the future. Another point that may be mentioned is improving module reliability. In conventional AWGs, where heat is regulated using a heater, etc., it is necessary, in order to maintain the AWG center wavelength constant, to keep the AWG chip at a temperature of 100 C or above, raising problems of thermal degradation of the adhesives used in module construction. Thus if an a thermal device can be fabricated, temperature maintenance will be rendered superfluous and reliability improved. Optical networks are widely used in modern communication systems. The use of optical devices with good characteristics such as wide bandwidth, compact size, high fabrication tolerance, stable output, polarization independence, low power loss, etc., is becoming more and more important. Arrayed waveguide gratings (AWGs) are the key devices for wavelength-division multiplexers/demultiplexers and wavelength routers in backbone optical networks. In recent years, fiber-to-the-home has been built gradually, the use of cyclic AWG in any wavelength bands is paid attention to and studied for its expansibility. However, the pass band is not flat-topped and the spectral response is not uniform for conventional cyclic AWG. Those require a light source of high accurate wavelength in order to have several signals with different wavelengths be multiplexed by an AWG and coupled into the same access fiber. In principle, the spectral response of cyclic AWG has a 3-dB no uniformity. Thus, variable optical attenuators are necessary to equalize the powers between the output signals. It would then be too expensive to use a variable optical attenuator for each channel in an AWG of 200 channels for commercial application. Therefore, flat-topped passband and uniformed spectral response are of great importance in order to have signals be equally multiplexed/demultiplexed by the same AWG and coupled into an access fiber [8]. To reduce the transmission loss, multimode interference (MMI) structures with taper access waveguides were reported in splitter and coupler applications. The arrayed waveguide grating (AWG) multiplexer is a key device for dense wavelength division multiplexing (DWDM) in optical telecommunication systems. An N x N AWG multiplexer can offer some basic functions including multiplexing, demultiplexing, routing and N x N interconnection. Polymer AWG devices possess some excellent particular features including easier fabrication and easier control of the refractive index compared with AWGs made of other materials. Recently, many research groups have focused on the development of polymer AWG multiplexers, and have fabricated such optical devices using various polymeric materials. Excellent AWG devices are dependent on accurate structural design and fine technological processing. However, fabrication errors are hard to avoid in the manufacturing of the AWG devices. Some previous papers also reported on the impact of fabrication errors on the transmission characteristics of AWG devices. Therefore, parameter optimization and fabrication error analysis are very important in the design and fabrication of AWG devices [9].

In the present study, the first step is the principle of the a thermal AWG with $LiNbO_3$/Polymer/Silica-doped hybrid materials is described, and the relative formulas are derived for analyzing and investigating parametrically and numerically the temperature dependence of the A thermal AWG module for passive and active optical network applications. Finally, a conclusion is reached based on the analysis and general discussion.

2. Low Loss A thermal Arrayed Wave-guide Grating Module

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 [8]. The AWG consists of input waveguides, arrayed waveguide, slab waveguide and output waveguides, constituting a diffraction grating that takes advantage of the optical path difference in the arrayed waveguide. As ambient temperature changes, the phase front at each wavelength generated by the arrayed waveguide will tilt due to the change in the refractive index of the optical waveguide and the linear expansion of the silicon substrate, causing a shift of the focusing point on the output waveguide within the slab waveguide [10]. As shown in Fig. 1, the thermal arrayed waveguide grating (AWG) with cross-sections is designed as square shape with the core width a, of lithium niobate ($LiNbO_3$) material and PMMA polymer overcladding and Silica-doped undercladding material on a silicon substrate.

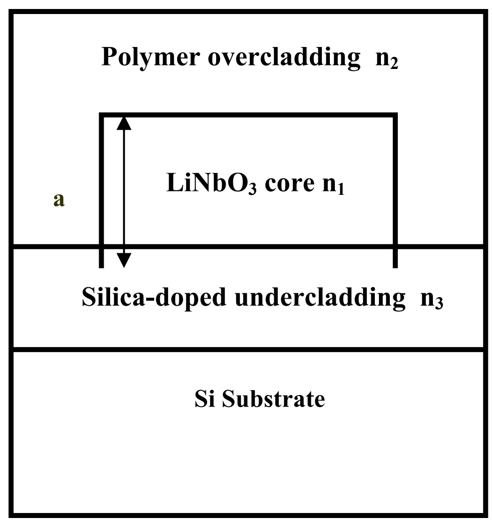

Figure 1. A structure view of cross-section and refractive- index profile of hybrid materials $LiNbO_3$/Polymer/Silica-doped.

3. Passive and Active Optical Network Features

Dense wavelength division multiplexing (DWDM) passive optical network systems, which had their origins in long-haul communication networks are now spreading to the entire world. They are also being used in Metro-networks and other short-range communication networks. The number of channels in DWDM systems is getting larger due to the unlimited need for transmission capacity in communication networks. In general, the greater the number of channels in a DWDM passive optical network system, the greater the power consumption of the system as a whole. Moreover, the increase in the number of optical components as system functions increase, and the use of high-power optical amplifiers means even greater power consumption of the optical network system. For this reason, there is an urgent need to reduce power consumption or eliminate electric power for individual optical components. AWGs are playing an important role as multiplexer/demultiplexers in DWDM systems. The AWG has design flexibility with respect to the number of channels and wavelength spacing, and is superior in mass productivity and compactness. It has the further advantage that chromatic dispersion is extremely low, making it suitable to suitable to high bit-rate (40 Gbps) systems. This suggests that AWG is promising for use in future DWDM passive optical network systems. With the increasing diversity of DWDM passive optical network systems in recent years, one of the needs facing the AWG, which handles the function of wavelength multiplexer/demultiplexer, is for a thermalization (temperature-independence) requiring no power supply. The advantages of a thermalization are, most obviously, elimination of the need for a power supply, plus the fact that there is no need to monitor the temperature of the AWG module. This would make it possible for the AWG module to be isolated from transmission devices inside an office and to be installed in a variety of locations having no power supply, making them able to satisfy the needs of the increasingly diversified optical communications networks of the future. Another point that may be mentioned is improving module reliability. In conventional AWGs, where heat is regulated using a heater, etc., it is necessary, in order to maintain the AWG center wavelength constant, to keep the AWG chip at a temperature of 70 C or above, raising problems of thermal degradation of the adhesives used in module construction. Thus if an a thermal device can be fabricated, temperature maintenance will be rendered superfluous and reliability improved. Because of their excellent features and potential applications, the a thermal arrayed waveguide gratings (AWG) have currently received considerable attention and have become key components in dense wavelength-division-multiplexing passive optical networks. The enormous growth in the demand of bandwidth is pushing the utilization of fiber infrastructures to their limits. To fulfill this requirement the constant technology evolution is substituting the actual signal wavelength systems connected in a point to point technology by dense wavelength division multiplexing (DWDM) systems, creating the foundations for the optical transport network (OTN). The objective is the deployment of a optical network layer with the same flexibility because it is more economical and allows a better performance in the bandwidth utilization. Optical add drop multiplexers are the simplest elements to introduce wavelength management capabilities by enabling the selective add and drop of optical channels. A DWMD and UW-WDM networks with a static OADMs may provide a reliable, cost effective and scalable network, since the static OADMs are based on low loss, low cost passive devices and does not need any power supply. An active optical network looks very similar to a passive optical network (PON), however, there are three main differences. First, instead of having passive, unmanageable splitters in the field, it uses environmentally hardened Ethernet Electronics to provide fiber access aggregation. Second, instead of sharing bandwidth among multiple subscribers, each end user is provided a dedicated pipe that provides full bi-directional bandwidth. Because of its dedicated nature, this type of architecture is sometimes referred to as point to point (P2P). The third architectural difference between PON and Active is the distance limitation. In a PON network, the furthest subscriber must within 10-20 km from the central office (CO), depending on the total number of splits (more splits=less distance). An active optical network, on the other hand, has a distance limitation of 80 km, regardless of the number of subscribers being served. The number of subscribers is limited only by the switches employed, and not by the infrastructures itself as in the case of PON.

4. Hybrid Materials Refractive-index Model

4. 1. Lithium Niobate ($LiNbO_3$) Core 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_1) is given below, Sellmeier equation is under the form [11]:

$$n_1^2 = A_1 + A_2 H + \frac{A_3 + A_4 H}{\lambda^2 - \left(A_5 + A_6 H\right)^2} + \frac{A_7 + A_8 H}{\lambda^2 - A_9^2} - A_{10}\lambda^2 \tag{1}$$

where λ is the optical wavelength in μm and $H = T^2 - T_0^2$. T is the temperature of the material, C, and T_0 is the reference temperature and is considered as 27 C. The set of parameters of Sellmeier equation coefficients, $LiNbO_3$, are recast and dimensionally adjusted as below [11]: 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 the following expression:

$$n_1^2 = A_{12} + \frac{A_{34}}{\lambda^2 - A_{56}^2} + \frac{A_{78}}{\lambda^2 - A_9^2} - A_{10}\lambda^2 \tag{2}$$

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 which gives:

$$\frac{dn_1}{d\lambda} = \left(\frac{-\lambda}{n_1}\right)\left[\frac{A_{34}}{\left(\lambda^2 - A_{56}^2\right)^2} + \frac{A_{78}}{\left(\lambda^2 - A_9^2\right)^2} + A_{10}\right] \tag{3}$$

Also, the differentiation w. r. t T gives:

$$\frac{dn_1}{dT} = \left(\frac{T}{n_1}\right)\left[A_2 + \frac{\left(\lambda^2 - A_{56}^2\right)A_4 + 2A_6A_{56}A_{34}}{\left(\lambda^2 - A_{56}^2\right)^2} + \frac{A_8}{\left(\lambda^2 - A_9^2\right)}\right] \tag{4}$$

4. 2. PMMA polymer over-cladding material

The Sellmeier equation of the refractive-index is expressed as the following [12]:

$$n_2^2 = 1 + \frac{C_1\lambda^2}{\lambda^2 - C_2^2} + \frac{C_3\lambda^2}{\lambda^2 - C_4^2} + \frac{C_5\lambda^2}{\lambda^2 - C_6^2} \tag{5}$$

The parameters of Sellmeier equation coefficients, PMMA, as a function of temperature [12]: C_1=0.4963, C_2=0.07180 (T/T_0), C_3=0.6965, C_4=0.1174 (T/T_0), C_5=0.3223, and C_6=9.237.

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

$$\frac{dn_2}{dT} = \frac{\lambda^2 (0.0718)}{n_2 \, T_0} \left[\frac{C_1 C_2}{\left(\lambda^2 - C_2^2\right)^2} + \frac{1.635 \, C_3 C_4}{\left(\lambda^2 - C_4^2\right)^2} \right] \quad (6)$$

4. 3. Silica-doped under-cladding material

The Sellmeier equation of the refractive-index is expressed as the following [13]:

$$n_3^2 = 1 + \frac{B_1 \lambda^2}{\lambda^2 - B_2^2} + \frac{B_3 \lambda^2}{\lambda^2 - B_4^2} + \frac{B_5 \lambda^2}{\lambda^2 - B_6^2} \quad (7)$$

The parameters of Sellmeier equation coefficients, silica-doped, as a function of temperature and Germania mole fraction, x, as follows [13]: 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.
Then the differentiation of Eq. (7) w. r. t T yields:

$$\frac{dn_3}{dT} = \frac{\lambda^2 (1.8954)}{n_3 \, T_0} \left[\frac{B_1 B_2}{\left(\lambda^2 - B_2^2\right)^2} + \frac{0.7654 \, B_3 B_4}{\left(\lambda^2 - B_4^2\right)^2} \right] \quad (8)$$

5. Modeling Basis and Analysis of A thermal Arrayed Waveguide Grating (AWG)

We present the a thermal condition and the relative formulas of $LiNbO_3$/Polymer/Silica-doped hybrid materials AWG on a silicon substrate. The temperature dependence of AWG center wavelength is expressed as [14].

$$\frac{d\lambda_c}{dT} = \frac{\lambda_c}{n_c} \left(\frac{dn_c}{dT} + n_c \, \alpha_{sub} \right) \quad (9)$$

where T is the ambient temperature, C, λ_c is the center wavelength of the arrayed waveguide grating, μm, n_c is the effective refractive-index of the arrayed waveguide grating, α_{sub} is the coefficient of thermal expansion of the Si substrate, and $\frac{dn_c}{dT}$ is the thermo-optic (TO) coefficient of the waveguide. By integrating Eq. (9), we can obtain the following expression:

$$\lambda_c = C \, n_c \, e^{(\alpha_{sub} T)} \quad (10)$$

where C is an integrating constant. Assume that $\lambda_c=\lambda_0$, and $n_c=n_{c0}$ when $T=T_0$ at room temperature, we can determine C as the following:

$$C = \frac{\lambda_0}{n_{c0}} e^{(-\alpha_{sub} T_0)} \quad (11)$$

Substituting from Eq. (11) into Eq. (10), we can obtain:

$$\lambda_c = \frac{\lambda_0 n_c}{n_{c0}} e^{[\alpha_{sub}(T - T_0)]} \quad (12)$$

From Eq. (12) we obtain the central wavelength shift caused by the temperature variation as:

$$\Delta\lambda = \lambda_c - \lambda_0 = \frac{\lambda_0}{n_{c0}} \left[n_c \, e^{(\alpha_{sub}(T - T_0))} - n_{co} \right] \quad (13)$$

Taking Δλ = 0, from Eq. (13) we can obtain the a thermal condition of the AWG as:

$$\alpha_{sub} (T - T_0) = \ln \left(\frac{n_c}{n_{c0}} \right) \quad (14)$$

The effective refractive index of the arrayed waveguide grating (AWG) is given by [15]:

$$n_c = \frac{\beta}{k} = \frac{k \left[\left(n_1^2 - n_2^2 - n_3^2\right) b + n_2^2 \right]}{k} = \left(n_1^2 - n_2^2 - n_3^2\right) b + n_2^2 \quad , \quad (15)$$

where β is the propagation constant of the fundamental mode, k is the wave number, and b is the normalized propagation constant and is given by [15]:

$$b\,(V) = \left(1.1428 - \frac{0.9660}{V} \right)^2 , \quad (16)$$

where V is the normalized frequency. For single mode step index optical fiber waveguide, the cut-off normalized is approximately V= V_c= 2.405, and by substituting in Eq. (16) we can get the normalized propagation constant b at the cut-off normalized frequency approximately b ≈ 0.5, and then by substituting in Eq. (15) we can obtain:

$$n_c = \frac{1}{2} \left(n_1^2 + n_2^2 + n_3^2 \right) \quad , \quad (17)$$

The cut-off normalized frequency for single mode step index optical fiber waveguide is given by the following expression [15]:

$$V_c = \frac{2\pi \, a}{\lambda_{cut-off}} \left(n_1^2 - n_2^2 - n_3^2 \right)^{1/2} \quad , \quad (18)$$

Assume that the cut-off wavelength is equal to the central wavelength to transfer the fundamental modes only, that is $\lambda_{cut-off}$ = λ_c. Eq. (18) can be expressed in another form as follows:

$$\lambda_c = \frac{1.45 \, \pi \, a \left(n_1^4 - n_2^4 - n_3^4 \right)^{1/2}}{2.405 \sqrt{n_c}} \quad , \quad (19)$$

Equation (19) can be expressed in another form as follows:

$$n_c = \frac{3.335 \, a^2 \left(n_1^4 - n_2^4 - n_3^4 \right)}{\lambda_c^2} \quad , \quad (20)$$

The effective refractive index n_c is dependent on the refractive indices of the hybrid materials and on the size and shape of the waveguide, then by selecting proper hybrid materials and structural parameters of the waveguide to satisfy Eq. (20), an a thermal arrayed waveguide grating (AWG) can be designed.

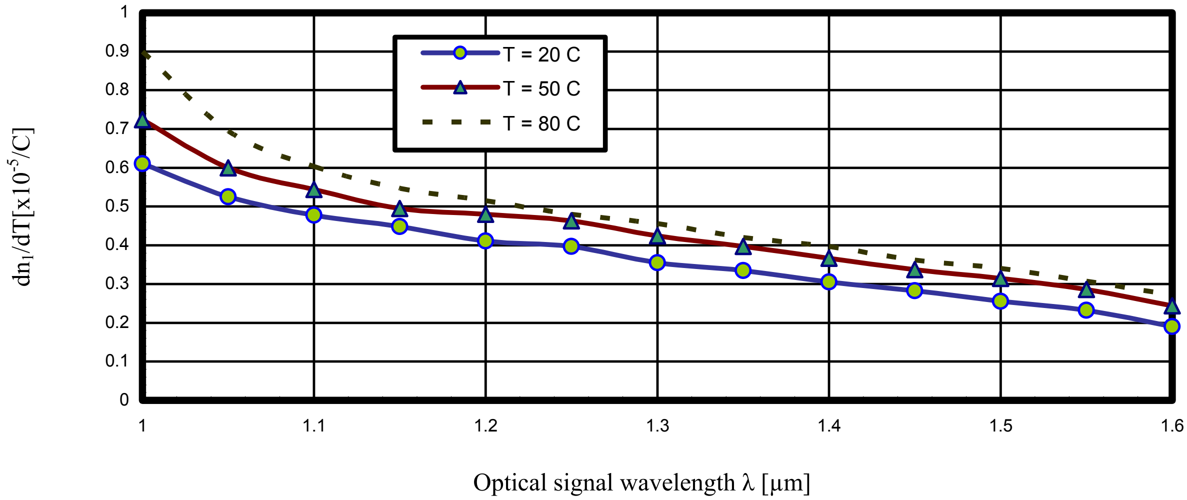

Figure 2. Variation of dn_1/dT versus wavelength for $LiNbO_3$ material.

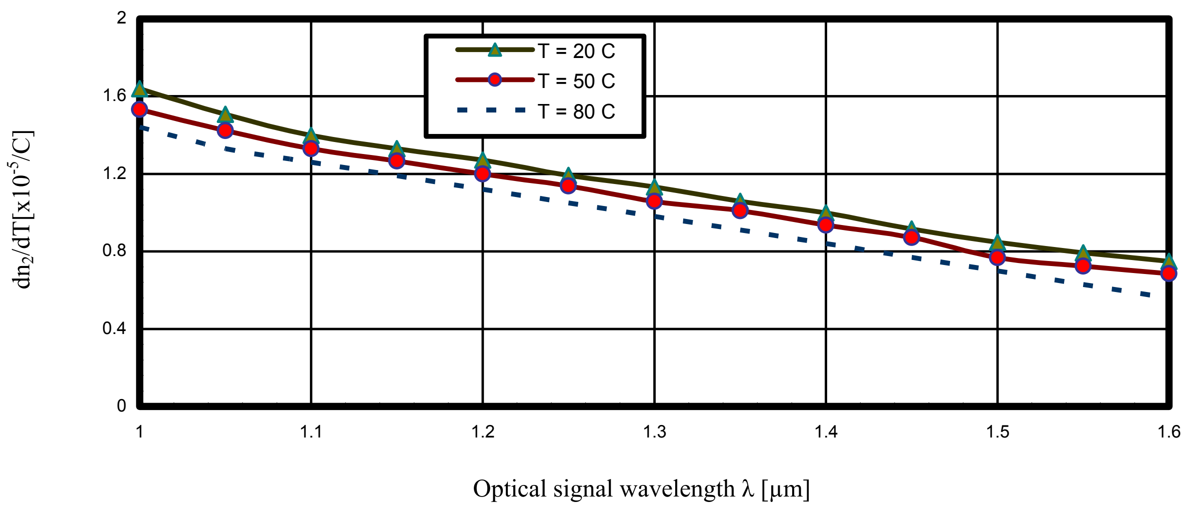

Figure 3. Variation of dn_2/dT versus wavelength for PMMA polymer material.

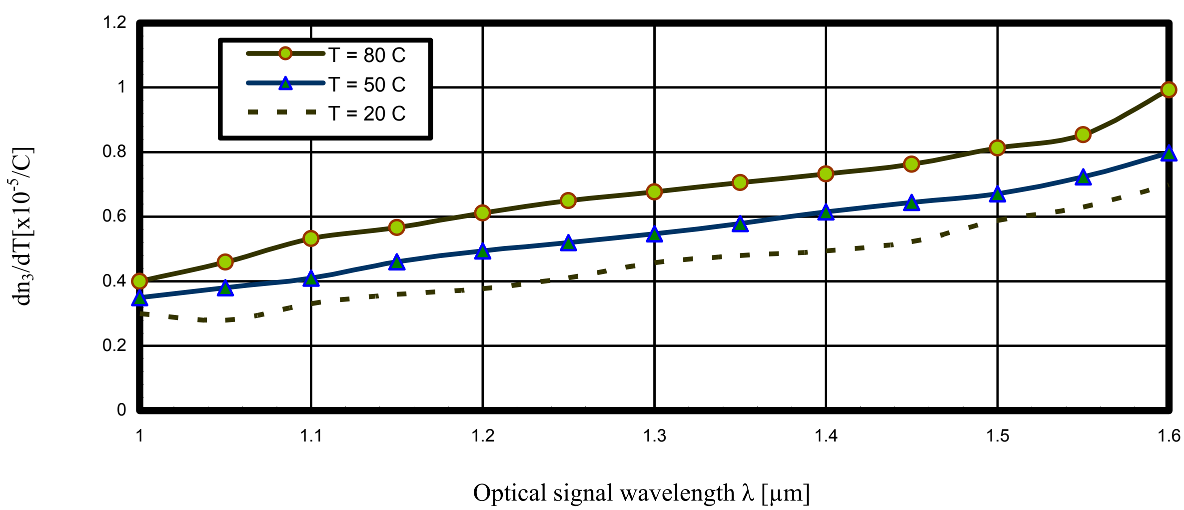

Figure 4. Variation of dn_3/dT versus wavelength for Silica-doped material.

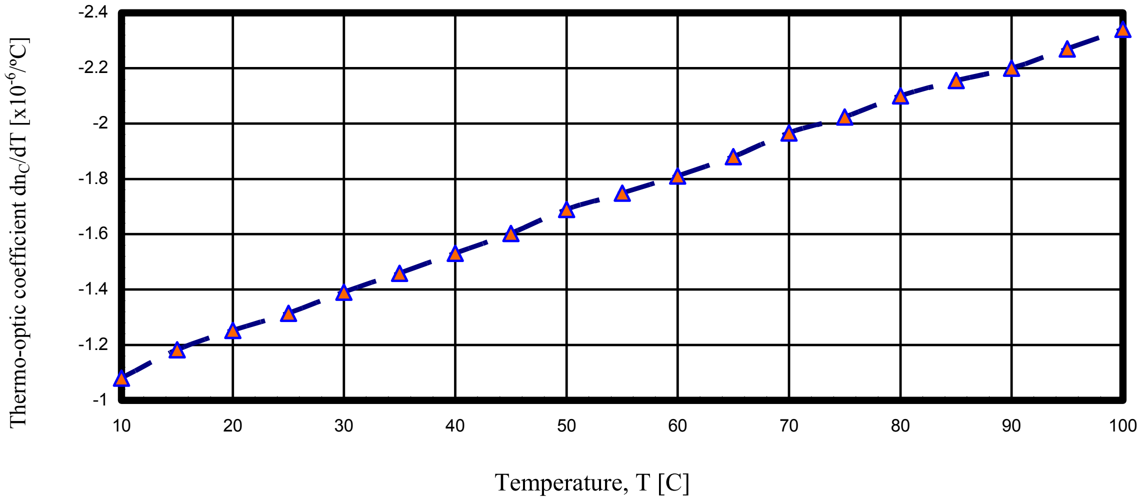

Figure 5. Variation of thermo-optic (TO) coefficient versus temperature when n_1=2.35, n_2=1.54, n_3= 1.49, a= 6 µm.

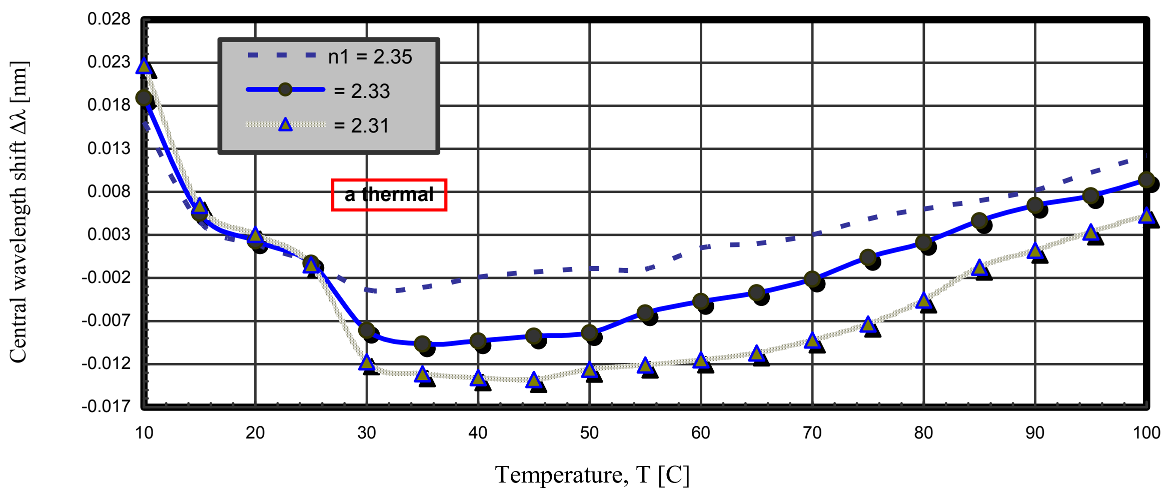

Figure 6. Variation of the central wavelength shift versus temperature for different core refractive-indices.

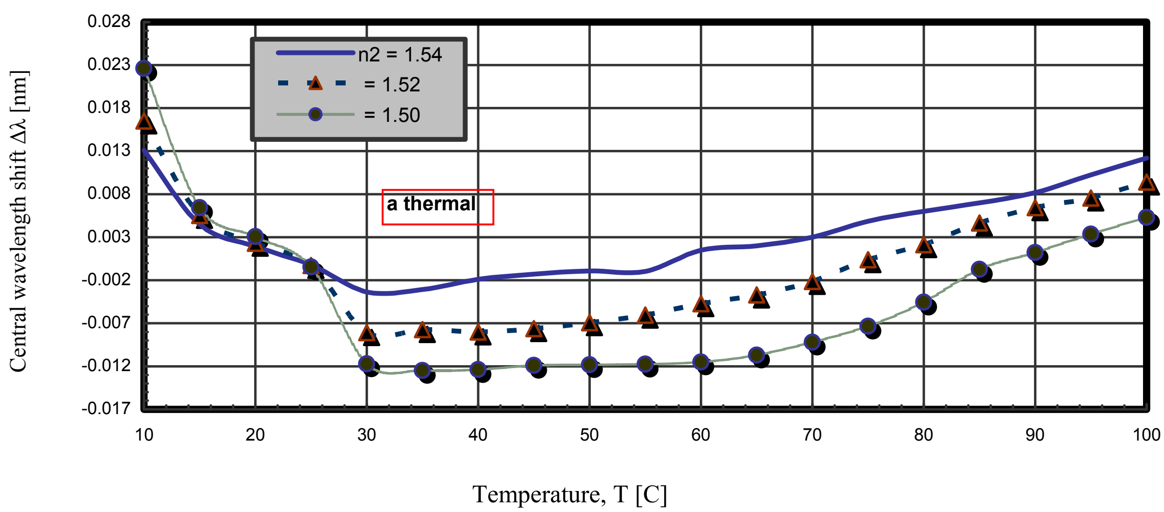

Figure 7. Variation of the central wavelength shift versus temperature for different overcladding refractive-indices.

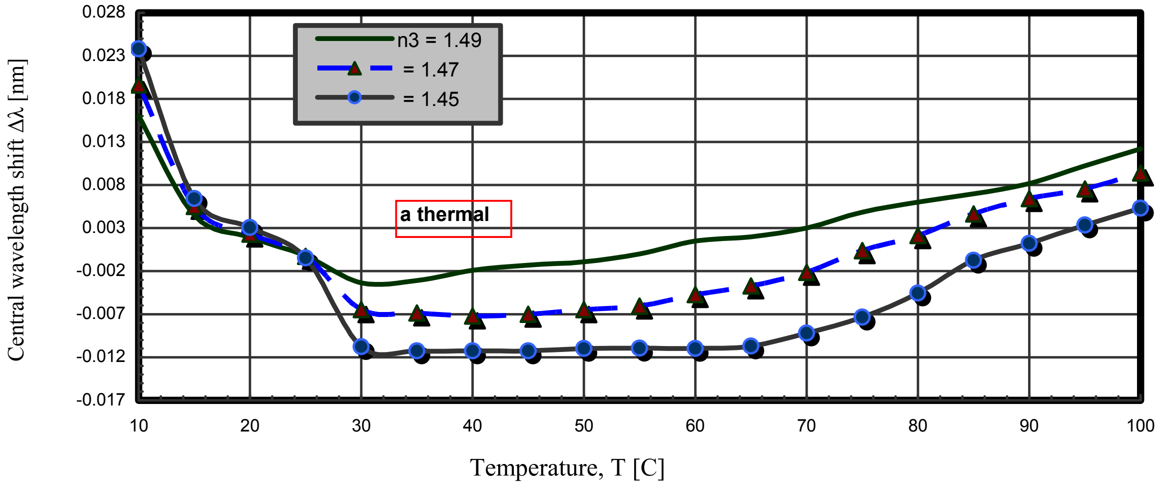

Figure 8. Variation of the central wavelength shift versus temperature for different undercladding refractive-indices.

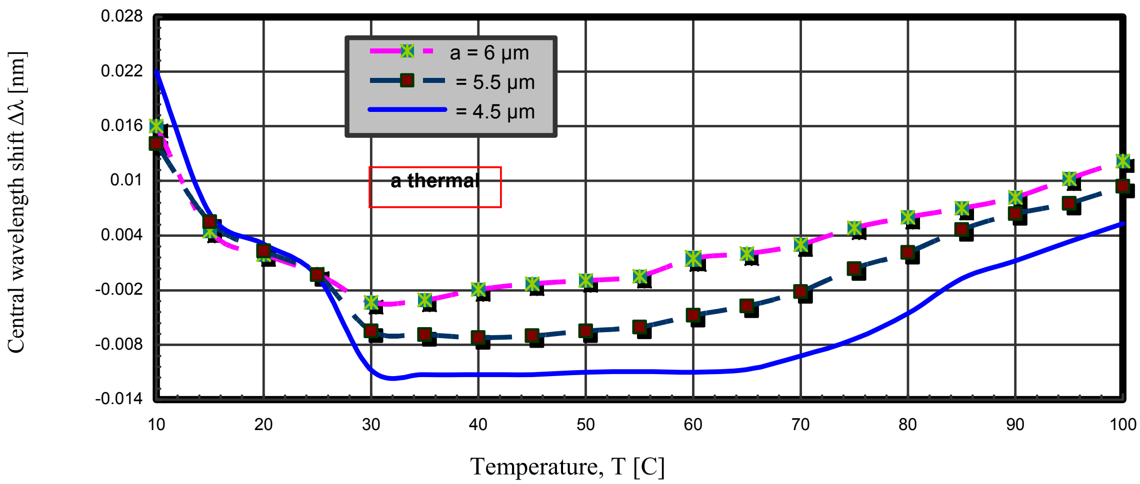

Figure 9. Variation of the central wavelength shift versus temperature for different core width of a thermal AWG.

6. Analysis of the Results

The center wavelength at room temperature T_0=27 C is selected to be λ_0= 1.550918 μm, which is one of the standard wavelengths recommended by the International Telecommunication Union (ITU) [16]. This AWG device is made on the silicon substrate have a coefficient of thermal expansion of α_{sub}= 2.63x10^{-6}/C [16]. Because the environmental temperature of an AWG is usually changed from 10 C t0 100 C. We discuss the central wavelength shift Δλ in this range of temperature variation. The subsequent relations between wavelength shift, and refractive-indices of core, and overcladding and undercladding n_1, n_2, n_3 as well as the core width **a** are discussed as follows.

1) As shown in Fig. 2, as the optical signal wavelength increases, the variation of refractive-index with respect to temperature decreases at the same ambient temperature. Moreover, as the ambient temperature increases, the variation of refractive-index with respect to temperature also increases at the same optical signal wavelength for $LiNbO_3$ material.
2) Figure 3 has indicated that as the optical signal wavelength increases, the variation of refractive-index with respect to temperature decreases at the same ambient temperature. While, as the ambient temperature increases, the variation of refractive-index with respect to temperature decreases at the same optical signal wavelength for PMMA polymer material.
3) Figure 4 has demonstrated that as the optical signal wavelength increases, the variation of refractive-index with respect to temperature increases at the same ambient temperature. Moreover, as the ambient temperature increases, the variation of refractive-index with respect to temperature also increases at the same optical signal wavelength for Silica-doped material.
4) Figure 5 has proved the dependence of the thermo-optic (TO) coefficient dn/dT on the temperature T. We can find that dn/dT is not constant with the variation of temperature which nonlinearly increases as temperature increases. Therefore, this behavior of dn/dT will obviously affect the shifts of the central wavelength caused by the variation of temperature.
5) As shown in Figs. (6-9) have demonstrated the dependence of the central wavelength shift Δλ on the refractive-indices of the core, overcladding, and undercladding n_1, n_2, and n_3 as well as the core width a for

the designed a thermal hybrid material AWG, which are calculated from Eq. (13). We can find that there exists an optimal operation condition of the AWG, which should guarantee the central wavelength shift Δλ to be small enough in a sufficiently large range of the temperature variation. To be precise, when we select n_1= 2.35, n_2=1.54, n_3=1.49 and a= 6 μm, the central wavelength shift is within the range of 0.023 ~ 0.016 nm as the temperature increases from 10 C to 100 C. In this case we can presume that the a thermalization is realized in the designed AWG.

7. Conclusions

In a summary, we have investigated parametrically and numerically the low loss a thermal arrayed waveguide grating of hybrid materials for suitable applications in passive and active optical networks. Moreover, we have presented a novel technique for theoretical model basis and optimum design of the a thermal AWG with $LiNbO_3$/Polymer/Silica-doped hybrid materials. By selecting the proper values of the refractive-indices of the hybrid materials and the core size of the waveguide, the a thermalization can be realized. To be precise, the central wavelength shifts of the our designed a thermal hybrid material $LiNbO_3$/Polymer/Silica-doped AWG only increases to 0.039 nm/C, while that of the conventional silica-based AWG increases to 0.69 nm/C, our designed a thermal hybrid material AWG showed a good performance with Δλ = ~ 0.039 nm/C over the temperature range of 10 C to 100 C.

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