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Ultra Wide Arrayed Waveguide Grating (AWG) Devices for Dense Wavelength Division Multiplexing Optical Communication Systems

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***Abstract*— To meet the exploding demand for Internet and broad-band services, dense wavelength-division-multiplexing systems have been extended from long-haul transmission systems to metropolitan and access area networks. In such systems, compact and conventional arrayed-waveguide grating multi/demultiplexers are required to reduce the cost of the systems. The evolution of broadband services will depend on the widespread deployment of optical communication systems. The deployment of such systems will in turn, help drive increased demand for additional capacity. In this world, service providers will have a growing need to be able to flexibly adjust capacity to accommodate uncertain and growing demand. This paper has proposed ultra wide AWG devices for dense wavelength division multiplexing (DWDM) optical communication systems that deeply studied over wide range of affecting parameters. Two multiplexing methods are applied, space division multiplexing (SDM) and DWDM, where 300 to 600 transmitted channels are processed to handle the product of transmission bit rate for planar waveguide cables of multi links using soliton transmission technique and maximum time division multiplexing (MTDM).**

***Index Terms*— Gratings, Optical Planar Waveguides, Integrated Optics, Waveguide Arrays, and DWDM**

I. INTRODUCTION

UBIQUITOUS broadband backbone and access networks are considered by many to be necessary for the Internet to realize its full potential. But there is only limited understanding of the technology required for end to end broadband Internet services in today's nascent multi services, multiprovider environment [1]. In the United States, the penetration of broadband services is growing rapidly, reaching 10 percent or more of all Internet households. Current consumer broadband services, however, still only offer at best about 1Mbit/sec per subscriber and many subscribers experience far lower data rates because of upstream congestion. Optical networking technologies hold the promise of unlocking these bandwidth bottlenecks and the potential of supporting mass market services that offer an order of magnitude or more improvement in bandwidth available to consumers. The implications of recent developments in optical networking technologies such as Dense Wavelength Division Multiplexing and optical cross-connect systems (OXC) for the development of next generation communications infrastructure. A preliminary cost model of an all-optical network making use of these technologies is compared to older optical networking architectures to highlight the increased flexibility and scalability inherent in the newer architectures. These technologies change the economics of broadband services, with important implications for industry structure and the sorts of service markets that could develop and indeed [2, 3], must develop if the Internet is to remain robustly competitive and retain its multiprovider. The development of broadband services has been hampered by endemic congestion. Because optical infrastructure is still relatively new and because capacity could only be added in relatively large increments, deploying optical solutions has been quite expensive. Service providers face the dilemma of investing in excess capacity ahead of current demand, or tolerating congestion until pent-up demand warrants investing in the next increment of capacity [4].

The use of waveguide division multiplexing systems is increasing rapidly and, in these systems, arrayed waveguide gratings (AWGs) play important roles as multiplexer/demultiplexers [5]. They offer compactness, high stability, excellent optical characteristics, and mass producibility. Until now, AWGs have been developed solely for telecommunication applications, so their wavelength range has been limited to 1.3–1.6 µm. However, for novel applications such as sensors. AWGs with a shorter wavelength range, including the visible wavelength range. This is because many materials and analyses have specific characteristics at these wavelengths. Until now, only theoretical consideration has been given to AWGs operating in the visible wavelength range [6]. One of the key advantages of AWGs is their ability to provide the fine wavelength resolution required for optical spectroscopic sensors designed to identify materials and analyses. This arises from the design flexibility of the waveguide layout and enables us to obtain arbitrary spectroscopic characteristics by changing the path length difference between neighboring arrayed waveguides and the focal length of the slab waveguides. Planar lightwave 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 [7], 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 [8]. 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 [9].

In the present study, we have deeply investigated the performance of dense wavelength division multiplexing optical communication systems greatly depends on the spectral characteristics of their components. One key component of DWDM communication systems is the arrayed waveguide grating, which can serve as a wavelength multiplexer and demultiplexer. In order to allow the concatenation of many such devices and reduce the need for accurate wavelength control, their filter response must approximate a rectangular function. The spectral response of the arrayed waveguide rating plays an important role in optical communication systems. Ideally the grating should have a rectangular transfer function to reduce the need for accurate wavelength control and achieve low crosstalk. As well as AWG is playing an increasingly important role in dense wavelength division multiplexing communication system. The regular AWG device consists of an arrayed waveguide region where all the individual waveguides are equally spaced on the adjacent ones have constant length difference at different locations affect the device potential capacity.

II. MODELING ANALYSIS

The investigation of both the thermal and spectral variations of the waveguide refractive index require Sellmeier equation under the form [10, 11]:

$$n^2 = 1 + \frac{p_1\lambda^2}{\lambda^2 - p_2^2} + \frac{p_3\lambda^2}{\lambda^2 - p_4^2} + \frac{p_5\lambda^2}{\lambda^2 - p_6^2} \qquad (1)$$

Where λ is the optical signal wavelength in μm. The parameters of empirical equation coefficients for silica based AWG devices, as a function of ambient temperature as: p_1= 10.668422193, p_2= 0.0301516485 $(T/T_0)^2$, p_3= 3.043474218x 10^{-3}, p_4= 1.1347511235$(T/T_0)^2$, p_5=1.54133408, p_6=1.104x10^3. Where T is the ambient temperature in K, and T_0 is the room temperature. The second differentiation of empirical equation w. r. t λ as in Ref. [11]. The total bandwidth is based on the total chromatic dispersion coefficient D_t where: D_t= D_m + D_w. Both D_m, and D_w are given by (for the fundamental mode):

$$D_m = -\frac{\lambda}{c}\left(\frac{d^2n}{d\lambda^2}\right), \ n\sec/m^2 \qquad (2)$$

$$D_w = -\left(\frac{n_{cladding}}{cn}\right)\left(\frac{\Delta n}{\lambda}\right)Y \ , \ n\sec/m^2 \qquad (3)$$

Where c is the velocity of the light, 3 x 10^8 m/sec, n is the refractive-index of the fiber cable core, Y is a function of wavelength, the relative refractive-index difference Δn is given by the following expression:

$$\Delta n = \frac{n - n_{clad}}{n} \quad , \qquad (4)$$

Soliton propagation as a real technique attracted the attention for long distance optical communication systems of high capacity [11]. Based on the model of [12], the condition to obtain sustained soliton is given by:

$$P_{so}\,\tau_{os}^2 = 0.597\left(\frac{\lambda}{1.54}\right)\left(\frac{A_e}{20}\right)\left(\frac{3.2x10^{-20}}{n_2}\right)\left|D_t\right| \ , \ \text{watt.nsec}^2 \qquad (5)$$

Where λ is the operating optical wavelength in μm, P_{so} is the average signal power in Watt, A_e is the effective area in μm^2, $|D_t|$ is the total chromatic dispersion coefficient in nsec/m^2, τ_{os} is the initial pulse width in nsec, and n_2 is the nonlinear refractive-index coefficient and is qual to 2.66x10^{-20} m^2/Watt. Taking into account that the pulse width at distance equals 10 $\tau_{os,}$, then the soliton transmission bit rate per channel is given by the following relation:

$$B_{rsc} = \frac{1}{10\,\tau_{os}} = \frac{0.1}{\tau_{os}} \ , \text{Gbit/sec/channel} \qquad (6)$$

To achieve a high data transmission bit rate in the telecommunication field is the goal of DWDM technology. The maximum bit rates are determined by numerous factors, including the signal modulation rate, the transmission bandwidth through the transmission media, and the response time of the optoelectronic devices. In optical communication systems, the DWDM system is simply one part of the transmission regime. The pulse broadening of grating-based DWDM imposes inherent limitations on the data transmission bit rates. According to our assumption that the standard single mode optical fiber cable is made of the pure silica material which the investigation of the spectral variations of the waveguide refractive-index (n) is shown in Eq. (5), Then the first and third differentiation of Eq. (1) w. r. t λ as discussed in Ref. [12]. The total chromatic dispersion in standard single mode fiber (SSMF) that limits the transmission bit rates in system based UW-WDM communication can be calculated as follows [14]:

$$D_t = \frac{\Delta\tau}{\Delta\lambda.\,L} = -\left(M_{md} + M_{wd}\right), n\sec/nm.km \qquad (7)$$

Where M_{md} is the material dispersion coefficient in nsec/nm.km, M_{wd} is the waveguide dispersion coefficient in nsec/nm.km, Δτ is the total pulse broadening due to the effect of total chromatic dispersion [13, 15], Δλ is the spectral linewidth of the used optical source in nm, and L is the fiber cable length in km. The material dispersion coefficient is given as:

$$M_{md} = -\frac{\lambda_s}{c}\frac{d^2n}{d\lambda^2} - \frac{\Delta\lambda}{2c}\left(\lambda\frac{d^3n}{d\lambda^3} + \frac{d^2n}{d\lambda^2}\right), \qquad (8)$$

The waveguide dispersion coefficient is given by the following expression [16]:

$$M_{wd} = -n_{cladding}\left(\frac{\Delta n}{c\,\lambda_s}\right)F(V), \qquad (9)$$

Where n_{clad} is the refractive-index of the cladding material, Δn is the relative refractive-index difference, λ_s is the optical signal wavelength, F(V) is a function of V number or normalized frequency. Based on the work [16], they designed the function F (V) is a function of V as follows:

$$F(V) = 1.38V - 6.98V^2 + 13.45V^3 - 4.84V^4 - 1.48V^5\ , \qquad (10)$$

When they are employing V-number in the range of ($0 \leq V \leq 1.15$) yields the above expression. In our simulation model design, we are taking into account V-number as unity to emphasis single mode operation. The MTDM transmission bit rate per channel can be expressed as follows [18]:

$$B_{rmc} = \frac{1}{4\Delta\tau} = \frac{0.25}{\Delta\tau}\ , \qquad (11)$$

III. SIMULATION RESULTS AND DISCUSSIONS

In the present study, we have deeply investigated the basic soliton and MTDM transmission techniques to transmit 300 to 600 channels based on dense wavelength division multiplexed technique, in the interval of 1.3 up to 1.6 μm wavelengths. For the reality from the points of view of the spectral dependences of the different fiber characteristics [19], we employ also the space division multiplexing (SDM) where 300 to 600 transmitted channels are divided into subgroups each subgroup has its own spectral characteristics with N_L= {4, 5, 6,…..……………….24 } Links. Where the series of the formulas are listed below:

$$\Delta\lambda_L = \Delta\lambda / N_L \equiv Link\ spacing \qquad (12)$$

$$\delta\lambda_s = \Delta\lambda / (N_{ch}\ N_L) = \Delta\lambda_L / N_{ch} \qquad (13)$$

$$|\delta f| = \delta\lambda / \lambda_{ave}^2\, c \qquad (14)$$

$$|\Delta f| = \left\{\Delta\lambda_L / N_{ch} * \lambda_{ave}^2\right\} c \qquad (15)$$

Where $c=3\text{x}10^8$ m/sec, N_{ch} ≡ Number of channels/link, N_L ≡ Total number of links/core, N_{ct} ≡ Total number of channels = 300–600 channels. Where $\Delta n = \Delta n_f - \Delta n_i = 0.009 - 0.005 = 0.004$, and $\Delta\lambda = \lambda_f - \lambda_i = 1.6 - 1.3 = 0.3$ μm.

$$\lambda_s(initial)/\,link = 1.3 + (JS - 1)\delta\lambda_s \qquad (16)$$

With JS ={1 , 2 , 3 …………………… N_L}. Where the suffix "f" denotes the final value and "i" denotes the initial value, λ_{ave} is the average wavelength over the link of order JS, JS is the order of the link where $1 \leq JS \leq N_L$, N_L is the total number of links, λ_{si} is the initial wavelength at the link JS, and λ_{sf} is the final wavelength at the link JS. Due to the nonlinear limitations [15], so that the signal power P_{so} must satisfies the inequality: i.e. ,

$$P_{so}\,\delta f \leq 500 / N_{ch}^2 \quad \text{watt. GHz} \qquad (17)$$

Also, the optical wavelength span $1.3 \leq \lambda$, μm ≤ 1.6 is divided into intervals equal to:

$$\Delta\lambda_0 = 0.3 / N_L\ , \ \ \text{μm/Link.} \qquad (18)$$

The average optical wavelength λ_{ave} over a link of order JS is:

$$\lambda_{ave} = 0.5\Delta\lambda_0 (JS + 1)\ \ , \qquad (19)$$

Based on the model equations analysis and the series of the assumed set of operating parameters listed below, the following facts that clarified in the series of Figs. (1–11): $1.3 \leq \lambda$, optical signal wavelength, μm ≤ 1.6, N_{ct}, total number of channels= 300–600 channels, $4 \leq N_L$, number of links ≤ 24 , $0.005 \leq \Delta n$, relative refractive index difference ≤ 0.009, 300 K $\leq$ Ambient temperature, T $\leq$ 330 K, and 0. 1 Watt $\leq P_s$, signal power $\leq$ 0.597 Watt.

i) Figs. (1, 2) have assured that as operating optical signal wavelength increases, this leads to increase in transmission bit rates using soliton and MTDM technique at constant relative refractive index difference. As well as relative refractive index difference decreases, this results in increasing of transmission bit rates at constant operating optical signal wavelength.

ii) As shown in Figs. (3, 4) have indicated that as number of links in fiber cable core increase, this results in increasing of transmission bit rate per each channel. But as number of transmitted channels increases, this leads to decrease in transmission bit rates using different transmission techniques.

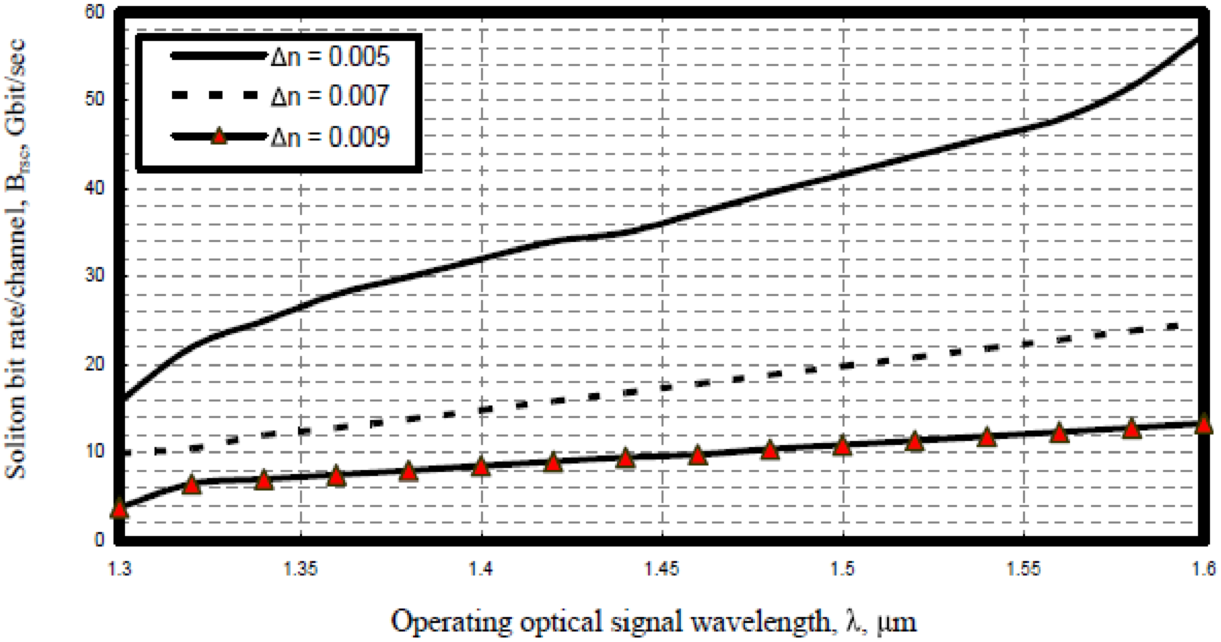

Fig. 1. Variations of soliton bit rate against operating optical signal wavelength at the assumed set of parameters.

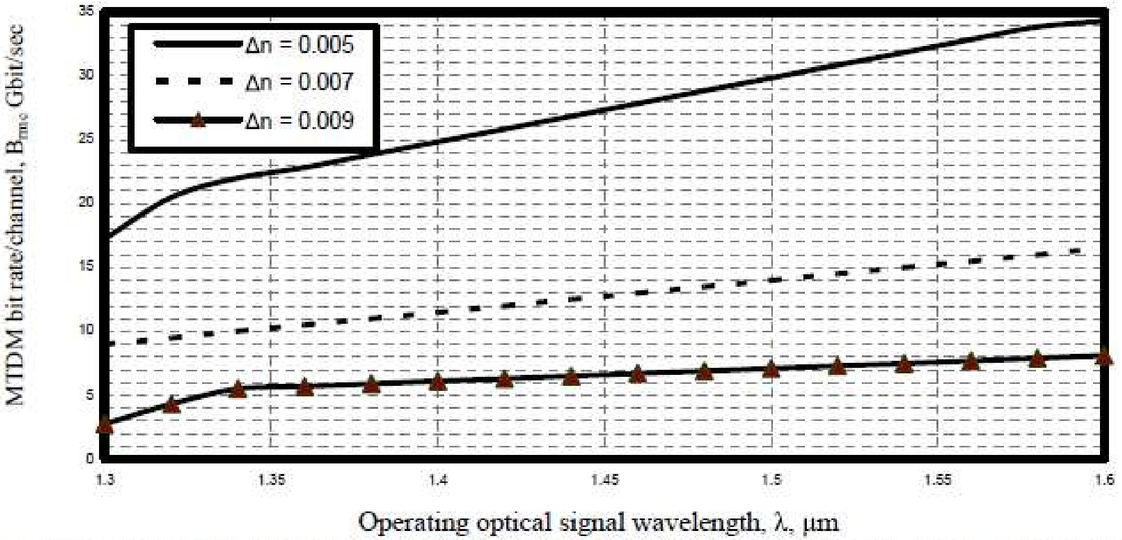

Fig. 2. Variations of MTDM bit rate against operating optical signal wavelength at the assumed set of parameters.

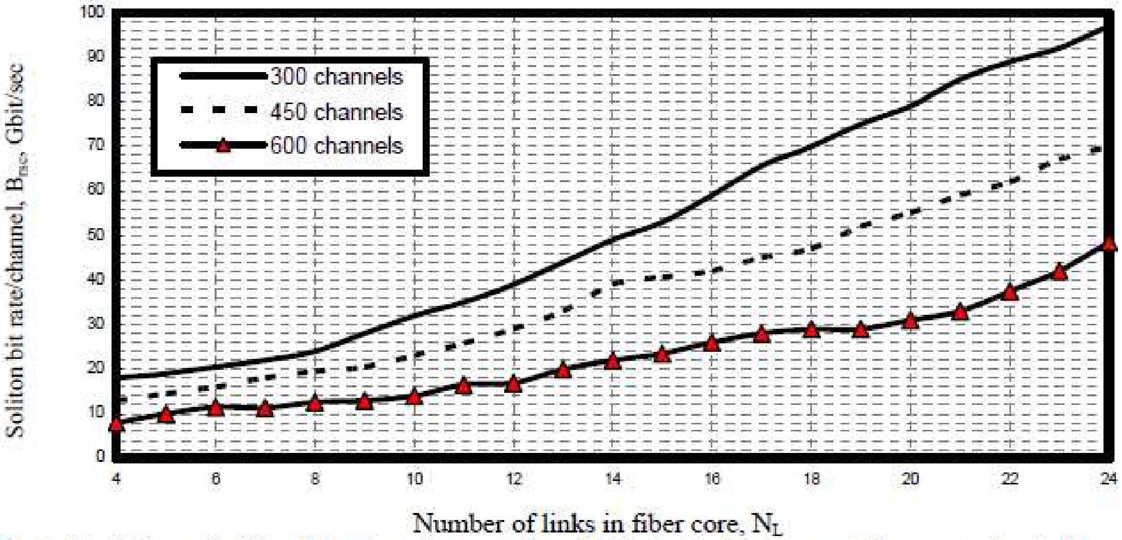

Fig. 3. Variations of soliton bit rate against number of links in the fiber core at the assumed set of parameters.

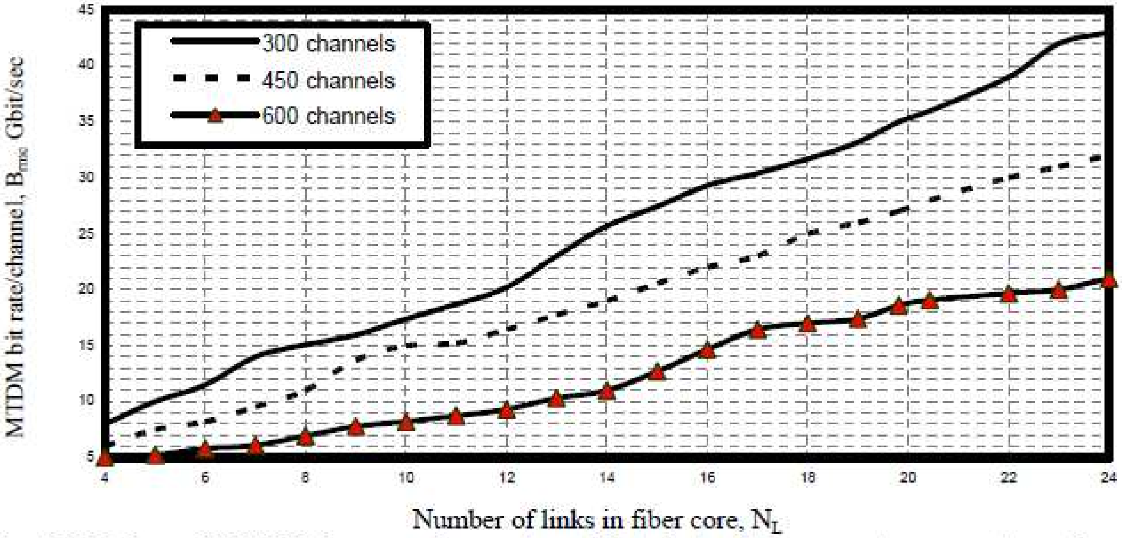

Fig. 4. Variations of MTDM bit rate against number of links in the fiber core at the assumed set of parameters.

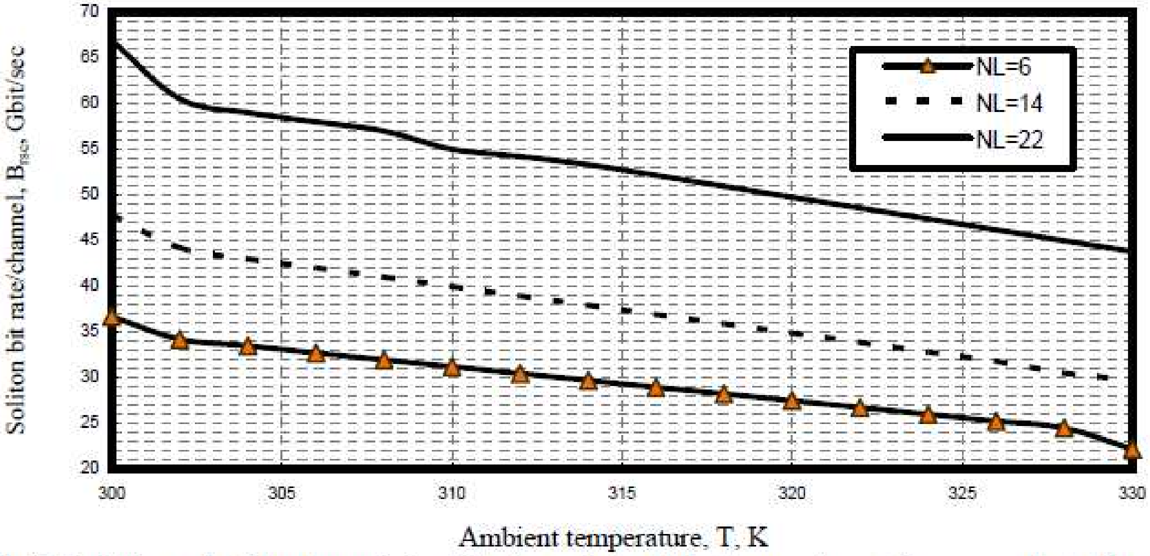

Fig. 5. Variations of soliton transmission bit rate against ambient temperature at the assumed set of parameters.

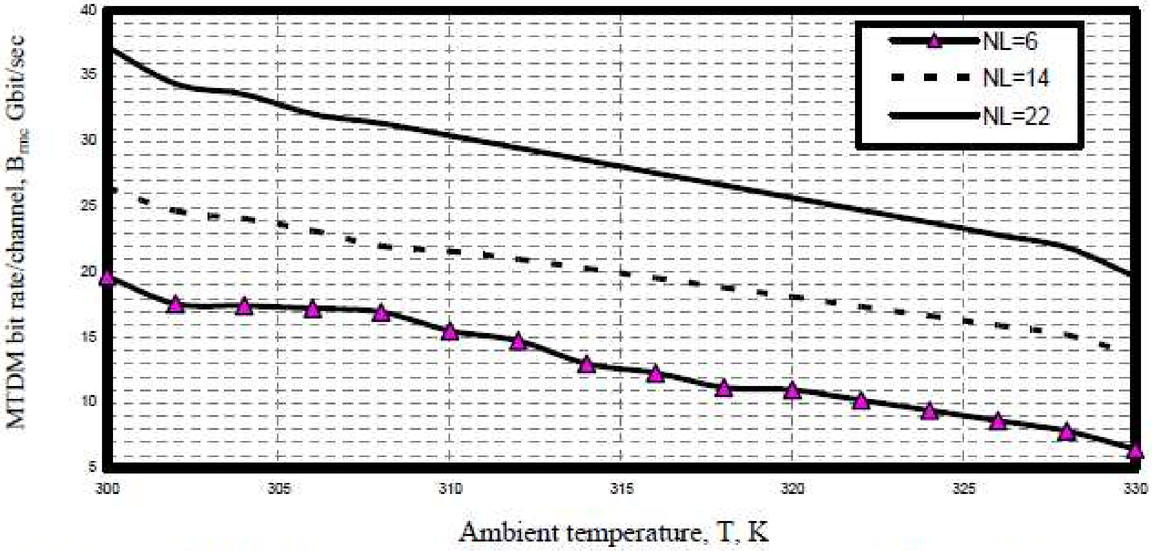

Fig. 6. Variations of MTDM transmission bit rate against ambient temperature at the assumed set of parameters.

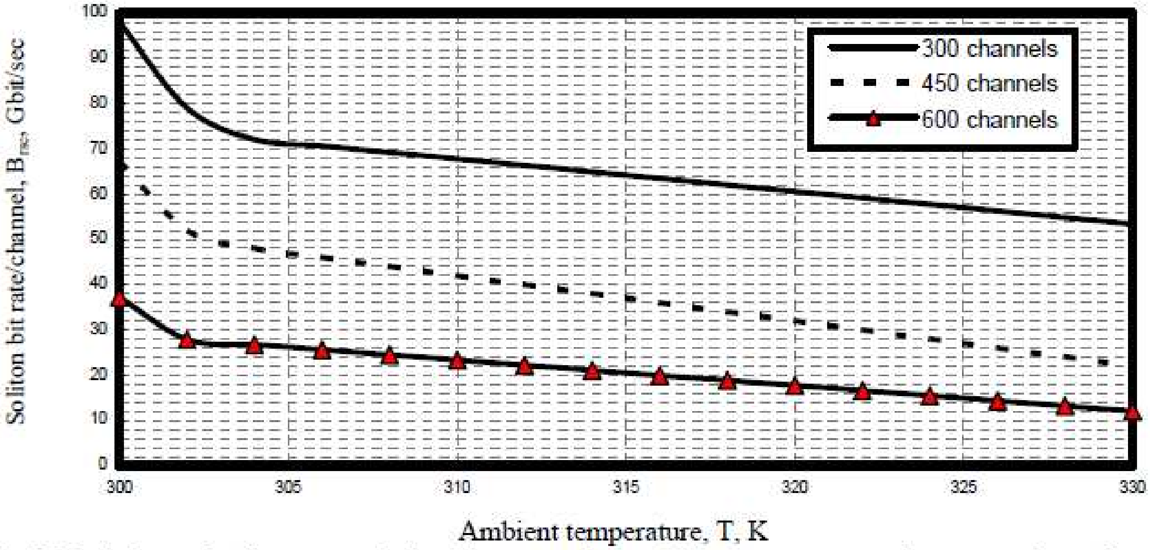

Fig. 7. Variations of soliton transmission bit rate against ambient temperature at the assumed set of parameters.

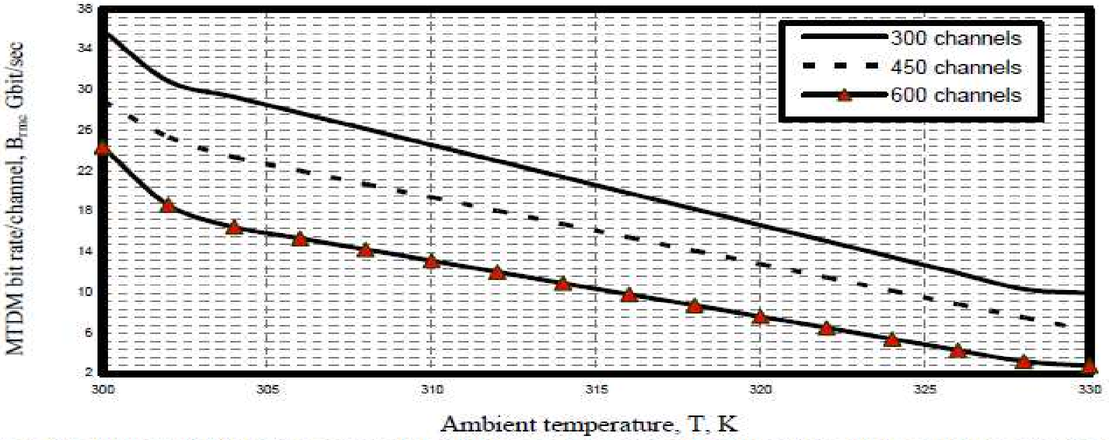

Fig. 8. Variations of MTDM transmission bit rate against ambient temperature at the assumed set of parameters.

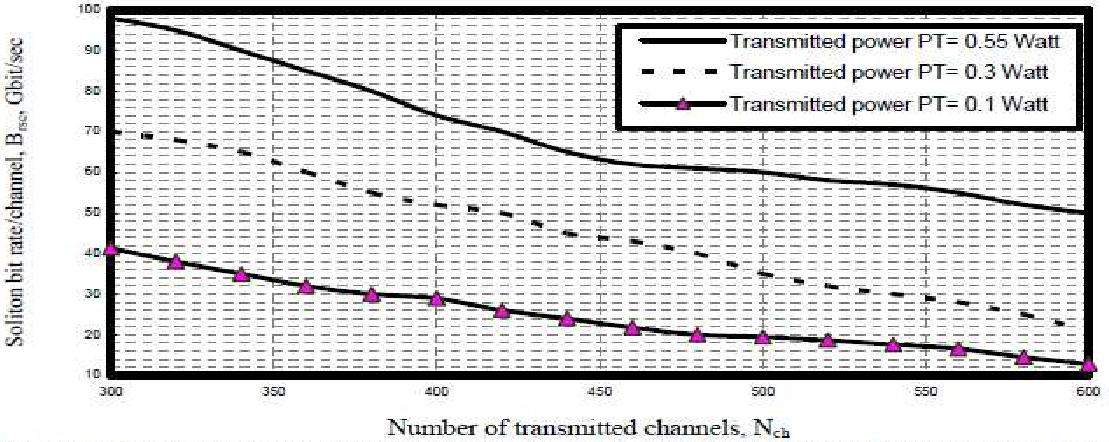

Fig. 9. Variations of soliton transmission bit rate against number of transmitted channels at the assumed set of parameters.

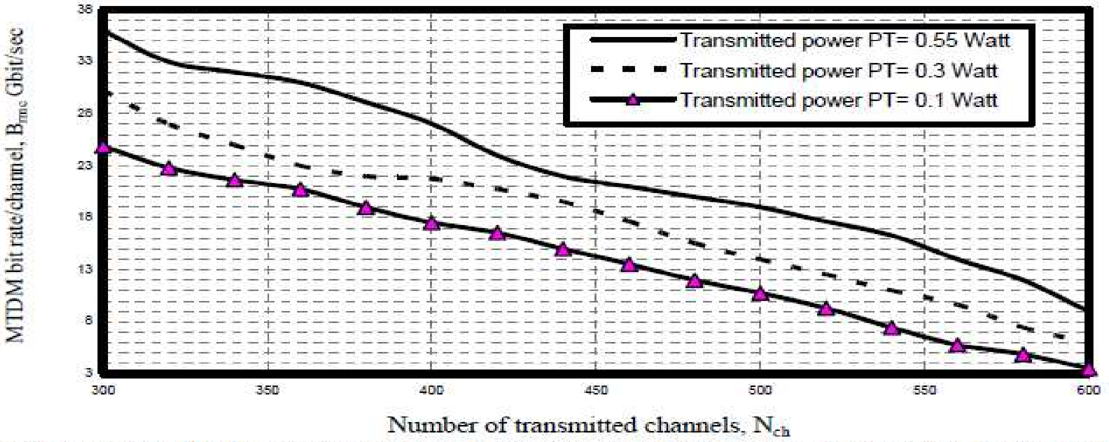

Fig. 10. Variations of MTDM transmission bit rate against number of transmitted channels at the assumed set of parameters.

iii) Figs. (5, 6) have demonstrated that as ambient temperature increase, this leads to decreases in transmission bit rates using different transmission techniques at constant number of links in the fiber cable core.

iv) As shown in Figs. (7, 8) have proved that as both ambient temperature and number of transmitted channels decrease, this leads to increase of transmission bit rates using different transmission techniques.

v) Figs. (9, 10) have assured that as transmitted signal power increases and number of transmitted channels decreases, this results in increasing of transmission bit rates using soliton and MTDM transmission technique.

vi) As shown in the series of Figs. (1-10) have demonstrated that the soliton transmission have presented higher transmission bit rates compared with MTDM transmission technique at the same operating conditions (number of transmitted channels, ambient temperature, relative refractive index difference, and transmitted signal power).

IV. CONCLUSIONS

This paper has developed ultra wide conventional arrayed waveguide grating devices based on two multiplexing techniques namely space division multiplexing and dense wavelength division multiplexing for increasing number of transmitted channels and also increases transmission bit rate per transmitted channels within each link. by using two transmission techniques namely soliton and MTDM. It is theoretically found that the decreased relative refractive index difference, and the increased operating optical signal wavelength, this leads to the increased transmission bit rate for each channel per link for different transmission techniques. As well as the increased of both transmitted signal power and number of links in the fiber core, and the decreased of both ambient temperature and number of transmitted channels, this results in increasing transmission bit rate for each subscriber. It is evident that the soliton transmission technique has presented higher transmission bit rates and high transmission capacity compared to MTDM propagation technique at the same operating parameters and conditions. AWG multi/demultiplexers, which have been developed for DWDM based optical communication systems. The AWG has already been used in point to point DWDM systems and is a key component in the construction of flexible and large-capacity DWDM communication systems. AWG offers the advantages of low loss, high port counts, and mass productivity. Further progress on the AWG is expected to contribute greatly to the construction of future photonic communication systems including optical add/drop multiplexing systems and optical cross connect systems.

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