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A Review on Arrayed Waveguide Grating Multiplexer/De-multiplexer forDense Wavelength Division Multiplexing Systems

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Abstract: Dense Wavelength Division Multiplexing (DWDM) is a fiber-optic transmission technique that employs light wavelengths to transmit data parallel-by-bit or serial-by-character. In DWDM system, the channels are very closely spaced. This technique has a high flexibility in expanding bandwidth and reducingthe cost of multiplexing and de-multiplexing. The three most commonly used devices namely Ring Resonator, Fiber Bragg Grating (FBG) and Arrayed Waveguide Grating (AWG) are employed for the purpose of multiplexing and de-multiplexing in a DWDM system. Among the three devices, AWG is widely in used these days because of its uniform channel spacing, better extinction ratio, reasonable bandwidth of pass-band and tolerable crosstalk. As a further matter, AWG has an advantage of decreasing price per channel with increase in the channel count. AWGs are very friendly to the CMOS environment hence can be easily fabricated with a very small footprint. The device is more convenient for the DWDM system design using various technologies such as multimode interference, silicon-on-insulator technology, optical lithography, germanium-on-silicon technology, etc.

Keywords: Arrayed waveguide grating, channel spacing, crosstalk, dense wavelength division multiplexing, insertion loss etc.

I. Introduction

To meet the expectation of the users that demands for a large capacity of data to be transferred with a greater speed, greater bandwidth is required. In order to fulfill these demands, optical communication is widely used these days because of its high speed, greater channel capacity, capability of long distance communication, greater bandwidth and lower power consumption, but transmission service of leased lines and packet switched networks are very expensive and hence leads to the need of multiplexing. Multiplexing divides the capacity of the low-level communication channel into several higher-level logical channels, for the transmission of each message signal or data stream. This technique is designed to reduce the number of electrical or optical connections for driving signals. In this technique, the different signals are transmitted through the same channel simultaneously by setting up one transmitter-receiver pair for each channel. Multiplexing technique permits hundreds and thousands of signals to be combined and transmitted over a single medium. This technique uses the bandwidth spectra very efficiently without wasting the bandwidth. It makes the communication system very economical and cost effective by increasing the capacity of the channel with a great transmission speed and a secured transmission of signals with less interference within the channels. Multiplexing technique can be either analog or digital in nature. Analog multiplexing comprises of Frequency Division Multiplexing (FDM) and Wavelength Division Multiplexing whereas Time Division Multiplexing is a type of digital multiplexing.WDM is further categorized into Coarse Wavelength Division Multiplexing (CWDM), Dense Wavelength Division Multiplexing (DWDM) and Ultra Wavelength Division Multiplexing (UDWDM).The WDM system comprises of various devices such as sources with stable narrow band emission wavelengths, tunable optical filters, add-drop filters, optical fiber, optical amplifiers, optical cross connects, wavelength inter-leavers and passive optical elements such as waveguides, arrayed waveguide gratings (AWGs), star couplers and grating devices.

To perform the function of multiplexing and de-multiplexing in the DWDM system, devices such as optical ring resonators, fiber Bragg gratings (FBGs) and arrayed waveguide gratings (AWGs) are used. Optical ring resonators and FBGs causes more coupling loss in the DWDM system and this is the reason why most of the DWDM systems uses AWGs as multiplexers and de-multiplexers for the channels. Though the device have few flaws such as insertion loss, channel crosstalk, polarization dependent loss etc.; it gives a cost efficient and high speed multiplexing and de-multiplexing for more number of channels.

II. Principle of Operation of Arrayed Waveguide Grating

Arrayed Waveguide Gratings (AWGs) is a semiconductor device having planar electrodes in parallel planes, made by alternate diffusion of p- and n- type impurities into a substrate withimaging and dispersive properties. AWGs canbe used as both Multiplexer and De-multiplexer unit. An AWG as shown in fig.1 consists of input-output waveguides, a bunch of arrayed waveguides and input-output Free Propagation Region (FPRs, also known as Star Coupler, designed based on Rowland circle geometry).

These devices are capable of multiplexing a large number of wavelengths into a single optic fiber, thereby increasing the capacity of transmission in optical networks. Their optical characteristic depends on the optical properties of the waveguide materials used. Based on the materials used AWGs can be designed either with Low-index-contrast or High-index-contrast. Among these High-index-contrast AWGs are mostly in use due to its high-refractive index difference between the core and the cladding.

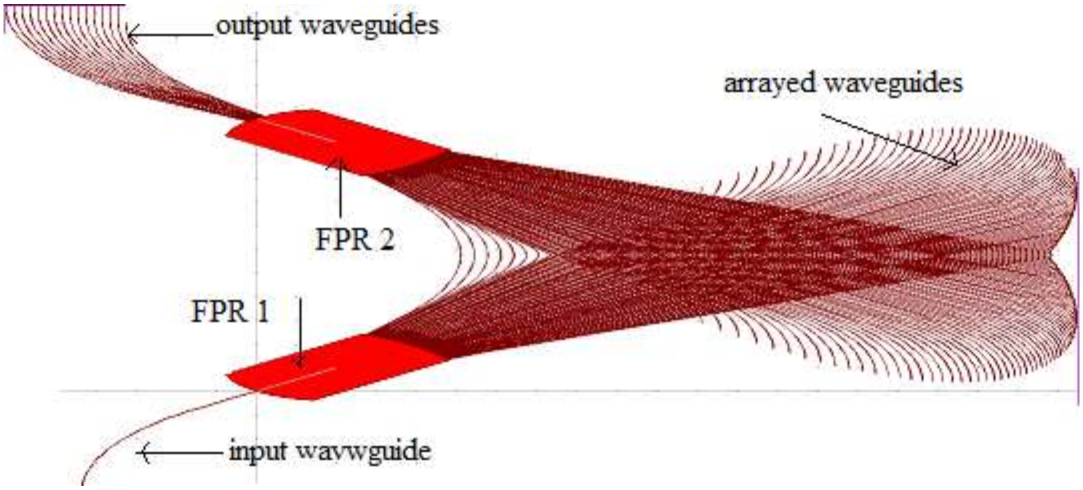

Fig.1: Arrayed waveguide grating

Based on the application, AWGs can be categorized on the basis of the number of transmitting channels, channel spacing and the spectral response. As the number of transmitting channels used to carry the information in WDM systems is generally a power of 2, the AWGs are designed to separate two different wavelengths (or 4, 8, 16, 32, 64 and so on). In addition AWGs with 40 and 80 channels are also available. The wavelength being used in transmitting channels are usually around the 1550 nm region because in this wavelength region optical fiber performs best due to very low losses. The various channel spacing that can be implemented using the device are 0.8 nm (also referred to as 100 GHz spacing); similarly, 1.6 nm (200 GHz) spacing; 0.4 nm (50 GHz) spacing; 0.2 nm (25 GHz) spacing.The system with narrow channel spacing, that is, 50 GHz and 25 GHz are classified for Dense Wavelength Division Multiplexing systems. As the demand for higher capacity continues to grow, it will be necessary to keep rising the channel counts for AWGs, thereby decreasing their channel spacing down to 0.1 nm (12.5 GHz) or 0.08 nm (10 GHz) or even less.

The input waveguide enters the lens region present in the FPR1 and propagates through it. It then divides the power among the different waveguides in the grating array. Each grating waveguide has a precise length difference ΔLas given in eq. 1 which is the path length and is greater than the previous one equal to the integer multiple of the center wavelength (λ_c) in the arrayed waveguide.

$$\Delta L = \frac{m\lambda_c}{n_{eff}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where,m is the order of grating, λ_c is the center wavelength and n_{eff} is the effective index of the arrayed waveguide. Light in each waveguide emerges with different phase delays $\Delta\varphi$ at the input of the FPR2. The second lens region refocuses the light from all array waveguides onto the output waveguide array. Each wavelength is focused into a different output waveguide and hence confined lights of different wavelength are separated.

The separation between the arrayed waveguides at the input FPR - arrayed waveguide junction and the output FPR – arrayed waveguide junction is very critical because of the following reasons:[8][9][10][11]

- As the separation between the arrayed waveguides and the FPR increases, more light gets radiated through that gap and the loss at the region of input FPR - arrayed waveguide junction increases.
- If the separation between the FPRs and the arrayed waveguides reduces, there occurs an unwanted coupling between the FPR and the arrayed waveguides which results in phase error.
- At the output FPR, the separation between the waveguides can be radially increased so as to lower the crosstalk between the two neighboring channels. But this separation leads to increase in the focal length of the output FPR as well as increase in the device footprint.
- In the arrayed waveguides, bent waveguides are incorporated in the device with varying bend radii to provide the required path length difference between the two neighboring waveguides.
- It is also important to determine that the bend radii should be as small as possible because larger the bend radii larger will be the bending loss in the waveguides.

III. Latest Research Work on Arrayed Waveguide Grating as Wavelength Division Multiplexers and De-multiplexers:

Various techniques and design parameters that are used to design anarrayed waveguide grating device for dense wavelength division multiplexing systems with varying performance of the devices from recent research and developments are discussed.

A compact wavelength division de-multiplexer device has been proposed [14]. The device comprises a bidirectional Arrayed waveguide Grating due to which it can achieve a doubled channel number at its output channels and a halved channel spacing. The device input has two input waveguides for connecting the bidirectional AWGs to the two output ports of the Mach-Zehnder Interferometer (MZI). Instead of using two AWGs they used bidirectional AWGs which resulted the device's footprint of approximately 520 µm × 190 µm which is about 50% smaller than the device that have two AWGs. The resultant of a 18-channel 200 GHz bidirectional de-multiplexer is discern to be similar in terms of crosstalk as a single 9-channel 400 GHz AWG which is approximately -18 dB but due to the cascading of MZI optical inter-leaver the corresponding excess loss of the device gets increased by 2 dB As a result the channel spacing of the device gets halved hence doubling the number of channels.

Design of a four-channel full-band wavelength division multiplexing (WDM) device based on multimode interference (MMI) on the material platform of silicon dioxide [15] is presented. Proposal of a waveguide structure based on silicon dioxide have been made. While designing the WDM multiplexer parameters were optimized such that the device shows the highest extinction ratio and a minimal insertion loss. Both the WDM multiplexer and the waveguide have been designed using RSOFT CAD Tool and have been simulated using beam propagation method (BPM) and finite-difference time-domain (FDTD). On the basis of optimized design parameters, the four-channel WDM multiplexer have been fabricated with a high bandwidth. The device can separate 1.28/1.34/1.52/1.58 µm wavelength signals. The proposed device have been successfully fabricated and tested. The device is suitable for integration with Si-based photonic devices.

Silicon based Arrayed waveguide grating with 100 GHz spacing using rib-waveguide with multimode interference coupler [16] is presented. The AWG device he designed contains 64 arrayed waveguides. The slab waveguide used is 212 µm long and the total size of the device is 850 µm wide and 1370 µm in length. The device consists of a single input channel and 8 output channels. At the slab waveguide to the arrayed waveguide interface an 1.5 µm wide aperture was used. To attain 100 GHz channel spacing the length difference of 32.7 µm was kept between the adjacent waveguides of the waveguide array. Waveguides with 200 nm thickness and width of 1 µm were used in the waveguide array. To examine the loss reduction structure, 3D-FDTD simulation process was used. It was observed that a low insertion loss of 2.8 dB has been achieved due to the use of simple rib-waveguide aperture using multimode interference (MMI) couplers which is among the lowest loss obtained in a 100 GHz channel spacing in silicon arrayed waveguide grating.

Methods for low crosstalk by presenting a design and experimental characteristic of an AWG to be used as a multiplexer/de-multiplexer with the configuration of 6 × 400 GHz channel spacing in a SOI based optical transport network [17] have been presented. The free propagation region is designed as a whiskered shaped so that reduction in the reflectivity of the star coupler can be investigated and how the arrayed waveguide grating's overall performance get affected by the FPR boundaries.

Silicon based low channel crosstalk arrayed waveguide gratings [18] is demonstrated. The AWG's free propagation region is connected to the single-mode input/output and arrayed waveguides using ultra-short parabolic tapers, linear tapers and exponential tapers. Using parabolic tapers it is realized that a satisfactory low-loss mode conversion and a lower channel crosstalk is caused due to the coupling of adjacent waveguides in the arrayed waveguide gratings. As a result, the AWG with parabolic tapers had a crosstalk improvement of about 7.1 dB as compared to the other tapers. Further he designed a 1.6 nm (400 GHz) channel spacing 8×8 cyclic arrayed waveguide gratings using parabolic tapers which had a maximum width of 1.9 µm and at a gap of 100 nm which resulted with -17.6~-25.1 dB crosstalk and 2.4 dB on-chip loss. The device has been fabricated using one step etching process successfully.

A novel high-index-contrast Si_3N_4 (silicon nitride) based arrayed waveguide grating [19] have been presented in which the device for very near-infrared wavelengths is designed. The device operates at 900 nm wavelength range. The AWG device has been successfully designed and fabricated with a channel spacing of 2 nm on a Si wafer coated with 2.6 µm oxide layer and depositing a 220 nm Si_3N_4 layer and etched into the substrate by the means of optical lithography. The device shows the lowest insertion loss of only -1.21 dB and exhibits the conventional and the cumulative crosstalk of 20 dB and 16.9 dB respectively. The device has a footprint of only 0.45 × 0.75 mm^2 and has the insertion loss non-uniformity of the device is -1.3 dB and has a 3-dB bandwidth as 0.59 nm. This device can be used for numerous on-chip applications to spectroscopy and optical sensing.

Comparison in the performance between the arrayed waveguide gratings and Echelle gratings for WDM system based on silicon-on-insulator platform [20] for different channel spacing and different values of free spectral region has been illustrated. Both the devices are compared on the basis of channel crosstalk, insertion loss and device footprint. The arrayed waveguide gratings has a measurement of 4×6.4 nm as footprint with channel crosstalk of -27.1 dB and an insertion loss of -1.53 dB, whereas the Echelle gratings has a 4×6.4 nm footprint with a crosstalk of -18.7 dB and an insertion loss of -1.43 dB. Several other dimensions of the devices have been studied and is found that the Echelle gratings are convenient for their use in Coarse Wavelength Division Multiplexing where the required channel spacing is larger, whereas, the arrayed waveguide gratings are convenient for their use in WDM and DWDM systems.

An AWG device on a germanium-on-silicon platform [21] has been demonstrated. The device operates in the range of 5 µm wavelength. In this range the device can be used as a wavelength multiplexer for mid-infrared light engines or as a core element of a mid-infrared spectrometer. The device is grown on an n-type Si substrate 0n 200 mm wafer with 2 µm thick epitaxial layer of germanium. Ge-on-Si based AWG with 200 GHz channel spacing and five channels is simulated using BeamPROP simulation tool and gives the waveguide losses in the range of 2.5-3.5 dB/cm for transverse electric (TE) polarized light and 3-4 dB/cm for transverse magnetic (TM) polarized light in the range of 5.15-5.4 µm wavelength. The other parameters measured results in an insertion-loss/crosstalk of 2.5/3.1 dB and 20/16 dB for TE and TM polarizations, respectively. The device can be used for optical sensing and as spectrometers.

A thermo-optically tunable silicon arrayed waveguide grating MUX/DE-MUX using TiN material [22] has been demonstrated. The device is designed using straight ridge-waveguide of width 0.8 µm-rib and narrow bended channel waveguide with width 0.5 µm. Two lensed fibers with 2.5 µm focal-length is used to characterize the optical performance of the device. For the designed 8 channel silicon AWG, the channel spacing used is 3.2 nm for which the optical loss achieved is approximately 5 dB. Above 600 GHz channel tenability is achieved for the device. The Si based device has an unwanted power consumption problem but it can be removed by 98% by replacing the underlying Si substrate with SiF_6 etching.

Spectrum-sliced wavelength division multiplexed passive optical network with the channel spacing of 25 GHz using 50 GHz arrayed waveguide gratings [23] is demonstrated. A pair of 50 GHz AWGs is used for the slicing of the spectrum, where AWG1 is for the even channels and AWG2 is for the odd channels.The presented 50 GHz AWGs spectrum-sliced WDM passive optical network gives a better bit error rate (BER) performance in both upstream and downstream directions than the conventionally used 25 GHz AWGs. The bandwidth of the demonstrated device increases by 14.9% whereas the BER decreases to 8×10^{-6} from 1.5×10^{-5} that of a 25 GHz AWG.

Ultra-compact silicon photonic 512×512 Arrayed Waveguide Grating Router with a channel spacing of 25 GHz [24] is presented. The dimension of the fabricated device is 16 mm × 11 mm and is fabricated on a 250 nm SOI platform. The device has the central wavelength 1.55 µm, path length difference of 6.011 µm, grating order 11, bend radius 85 µm and number of 512 input/output channels. The device is fabricated on 6 inch SOI wafer which consist of a 250 nm thick top silicon layer and a 2 µm BOX. The sample goes through a baking period of 60 seconds at 130° C. the measured channel crosstalk is approximately -4 dB which is quite high and can further improved with optimized fabrication process.

Alow-loss, low-crosstalk, and compact arrayed waveguide gratings based on a 200-nm-thick-Si3N4-core platform [25] is designed and implemented. High- resolution fabrication processes realized four types of Si3N4 AWG devices: 8 channel × 200 GHz, 16 channel × 100 GHz, 16 channel × 50 GHz, and 16 channel × 25 GHz AWGs. The measured channel spacing matched well with the design parameters. The RMS phase errors of the arrayed waveguides were π/6 and π/40 for the 16 × 25 GHz and 16 × 50 GHz AWGs. The devices footprints were 1.8 × 0.6 mm2, 2.2 × 0.7 mm2, 3.7 × 0.7 mm2, and 6.8 × 0.7 mm2 for the 16 × 100 GHz, 16 × 50 GHz, and 16 × 25 GHz AWGs, respectively. Low loss of (1.5 to 2.7) dB and low crosstalk of (-24 to -13) dB AWGs with various channel spacing was reported by them.

The techniques and materials used to design AWG for DWDM systems along with its design parameters and findings are described in Table 1:

Table 1: Various techniques and materials used to design arrayed waveguide grating for wavelength division multiplexing

Techniques	Material used	Parameters	Findings
Integration of bi-directional Arrayed Waveguide Grating with asymmetrical Mach-Zehnder Interferometer-based interleaver[14]	• Core: Silicon • Cladding: Silicon dioxide	• Bidirectional (N×+1) × (N+1) AWG • 18 channels • 200 GHz channel spacing	• Channel crosstalk = -15 dB • Excess loss increased by 2 dB • Device footprint decreased by approximately 50%
Full bandwidth WDM DE-MUX based on multimode interference (MMI)[15]	• Silicon dioxide waveguides	• Input waveguide width = 4 µm • Coupled waveguide width = 12 µm • Coupled waveguide length 1843 µm	• The device works as a 4-channel full-band WDM • Can separate 1.28 µm, 1.34 µm, 1.52 µm and 1.58 µm signals

Hundred GHz spacing Si AWG using rib-waveguide MMI[16]	• Core: Silicon • Cladding: Silicon dioxide	• 8 Channel AWG • 100 GHz channel spacing	• Device shows the minimum insertion loss of 2.8 dB • On caparison with a device using taper structure, a loss improvement of 1.3 dB was obtained
Silicon-on-insulator based optical transport network[17]	• Silicon on substrate of buried oxide layer	• Number of channels = 6 • Channel spacing = 400 GHz • Whiskered-shaped star coupler	• Insertion loss = 2.9 dB • Non-uniformity = 1.3 dB • Crosstalk = -20.6 ± 0.1 dB
Ultra-short parabolic tapers used in AWG to lower channel crosstalk[18]	• Silicon on substrate of buried oxide layer	• 8×8 cyclic AWG • Channel spacing = 400 GHz • Parabolic tapers with varying lengths from 1.0 µm to 6.0 µm	• Output power loss = 2.4 dB • Crosstalk = -17.7 ~ -25.1 dB
Silicon nitride based AWG for near-infrared wavelengths using optical lithography[19]	• Core: Silicon nitride • Cladding: Silicon dioxide	• Number of AWG channels = 12 • Channel spacing = 0.5 nm, 1 nm and 2 nm • 220 nm silicon nitride layer on silicon wafer	• Insertion loss for 0.5 nm = -3.99 dB, 1 nm = -2.26 dB and 2 nm = -1.21 dB among which for 2 nm channel spacing is the least • Insertion loss = -1.3 dB • Crosstalk = 16.9 dB
Comparison between AWGs and Echelle gratings for WDM[20]	• Silicon-on-insulator	• Arrayed waveguide gratings i. Channel spacing = 6.4 nm ii. Number of channels = 4 and 8 for box-shape AWG • Echelle gratings i. Channel spacing = 6.4 nm and 10 nm ii. Number of channels = 4	• Arrayed waveguide gratings i. Insertion loss = -1.53 dB and -1.86 dB for 4 and 8 channel AWG respectively ii. Crosstalk = -27.1 dB and 27.3 dB respectively for 4 and 8 channel AWG • Echelle gratings i. Insertion loss = -1.43 dB and -1.6 dB for 6.4 nm and 10 nm

			channel spacing of AWG ii. Crosstalk = -18.7 dB and -24.2 dB for 6.4 nm and 10 nm channel spacing of AWG
Germanium-on-silicon technology for mid-infrared AWG multiplexers[21]	• Core: Germanium • Cladding: Silicon	• Number of channels = 5 • Channel spacing = 200 GHz • 2 µm thick epitaxial layer grown on n-type silicon substrate • Operating wavelength of the device 5 µm	• Transverse electric polarization i. Waveguide loss = 2.5 dB/cm to 3.5 dB/cm ii. Insertion loss = 2.5 dB iii. Crosstalk = 20 dB • Transverse magnetic polarization i. Waveguide loss = 3 dB/cm to 4 dB/cm ii. Insertion loss = 3.1 dB iii. Crosstalk = 16 dB
Thermo-optically tunable silicon AWG MUX/DE-MUX [22]	• Core: Silicon • Cladding: Silicon	• Straight ridge-waveguide • Ridge-waveguide width = 0.8 µm • Channel waveguide width = 0.5 µm • Two lensed fiber with focal length = 2.5 µm • Number of AWG channels = 8 • Channel spacing above 600 GHz	• Reduced impact of fabrication non-uniformity on effective refractive index of AWG is achieved • Uniform heating is achieved by heater design • Above 600 GHz channel tunability is achieved • Optical loss = ~5 dB • Power consumption is reduced by utilizing optimization method
• Passive optical network using spectrum-sliced WDM • Channels modulated in 1.25 with a 2^{31}-1 pseudorandom bit	• Not available	• Two 50 GHz channel spaced AWGs for even and odd channels separately • Spectrum sliced channels = 1533.3 nm, 1533.5 nm and 1533.7 nm • Central channel is	• 25 GHz spaced spectrum-sliced WDM passive optical network using 50 GHz AWGs is achieved • Bit error rate of the device decreased by 8×10^{-6} from 1.5×10^{-5} at -23 dBm received power

sequence[23]		provided by using erbium doped fiber amplifier without input • Semiconductor optical amplifier input power = -7 dBm	
512 × 512 GHz AWG router using ultra-compact silicon photonics[24]	• Silicon on substrate of buried oxide layer	• Number of input channels = 512 • Number of output channels = 512 • Channel spacing = 25 GHz • Footprint of AWGR = 16 mm × 11 mm • Fabrication platform used 250 nm silicon-on-insulator	• Yielded waveguide loss during fabrication = 0.92 ± 0.14 dB/cm • Coupling loss = 11.3 dB • Channel crosstalk = -4 dB
Low-loss compact silicon nitride AWGs for photonic integrated circuits[25]	• Core: Silicon nitride • Cladding: Silicon dioxide	• Number of channels in AWGs = 8 and 16 • Channel spacing = 200 GHz, 100 GHz, 50 GHz and 25 GHz • Silicon nitride platform = 200 nm	• RMS phase errors of arrayed waveguides for 16×25 GHz = $\pi/6$ and 16×50 GHz = $\pi/40$ • Footprint of the device i. 16×100 GHz = 1.8×0.6 mm^2 ii. 16×50 GHz = 2.2×0.7 mm^2 iii. 16×25 GHz = 3.7×0.7 mm^2 iv. 8×200 GHz = 6.8×0.7 mm^2 • Loss in AWG = 1.5 dB to 2.7 dB • Channel crosstalk in AWG = -24 dB to -13 dB

From the extensive literature survey related to the development and designing of arrayed waveguide gratings, it is concluded that it is an efficient device for the DWDM system. The device can separate and accumulate a large number of channels at the receiver and transmitter ends respectively. The device is developed using various materials and different techniques. Each development technique of the device shows variations in its parameters such as losses, crosstalk, bandwidth etc. A technique using bidirectional arrayed waveguide grating is found more attractive technology for a system design as it can reduce the device footprint to a large extent and hence reducing the power consumption of the device.

IV. Conclusion

The basic need behind the study is to develop an AWG device using various techniques that can give a better performance in WDM systems. The effect of various parameters such as the material used, waveguide dimensions, number of arrayed waveguides, bend radius of arrayed waveguides, distance between the free propagation region and arrayed waveguides and effective refractive index are important to develop an AWG device. Varying the above stated parameters a better AWG device can be designed and developed that can give us more accurate results as per our expectations in terms of tolerable crosstalk, lower losses, least footprint and a least performance degrading AWG device that can be used in photonics integrated circuits for a better communication system.

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