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*Review*

# Estimated optimization parameters of arrayed waveguide grating (AWG) for C-band applications

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**In the present paper, we will investigate theoretically the basic design parameters of silica-based arrayed waveguide grating (AWG) in the C-band's spectral range (from 1.528 to 1.56 µm). We have demonstrated theoretically that the minimum the diffraction order m, the maximum the number of the input/output wavelength channels, and the maximum the number of the arrayed waveguides. Also, we have investigated the optimization design parameters of AWG for C-band applications.**

**Key words:** Silica-based AWG, wavelength multiplexer, wavelength demultiplexer, dense wavelength division multiplexing (DWDM), free spectral range (FSR).

## INTRODUCTION

In recent years, arrayed waveguide gratings (AWG), also known as the optical phased array-phasor, phased-array waveguide grating (PAWG), and waveguide grating router (WGR) have become increasingly popular as wavelength multiplexers/demultiplexers (MUX/DeMUX) for dense wavelength division multiplexing (DWDM) applications (Vellekoop and Smit, 1991). This is due to the fact that AWG-based devices have been proven to be capable of precisely demultiplexing a high number of channels, with relatively low loss. Main features of the N (input) x N (output) AWG MUX/DeMUXes are low fiber-to-fiber loss, narrow and accurate channel spacing, large channel number, polarization insensitivity, high stability and reliability, and being suitable for the mass production (Dragone, 1991). Because the fabrication of the AWG is based on standardized photolithographic techniques, the integration of the AWG offers many advantages such as compactness, reliability, large fabrication tolerances (no vertical deep etching), and significantly reduced fabrication and packaging costs. The inherent advantages of the AWG also include precisely controlled channel spacing (easily matched to the ITU grid), simple and accurate wavelength stabilization, and uniform insertion loss (Koteles, 1999).

Currently, arrayed waveguide grating (AWG) multiplexers (Jeong et al., 2005; Le and Chiao, 2005;Hirota et al., 2005; Jia et al., 2005; Kamei et al., 2005) are being developed greatly because of their wide applications to dense wavelength division multiplexing (DWDM) in optical communication systems, such as multiplexing, demultiplexing, routing and N×N interconnection. Recently, some research groups have focused on the research of silica, and polymeric AWG multiplexers, and have fabricated some such devices using various silica and polymeric materials, which possess excellent particular features including easier fabrication and easier tuning of the refractive index, compared with some other material AWG devices (Toyoda et al., 1999; Lee et al., 2001; Keil, and Lee, 2001; Park, and Lee, 2004; Lee et al., 2004)

In the present study, we have investigated theoretically the basic design parameters of silica-based arrayed waveguide grating (AWG) in the C-band's spectral range (from 1.528 to 1.56 µm). Also, we have analyzed the optimization design parameters of AWG for C-band applications.

### Basic operation principle of AWG device model

Generally AWG devices serve as multiplexers, demultiplexers, filters, and add-drop devices in optical WDM and DWDM applications. Figure 1 shows a schematic representation of the N x N AWG. The device consists of two concave slab waveguide star couplers (or free propaga-

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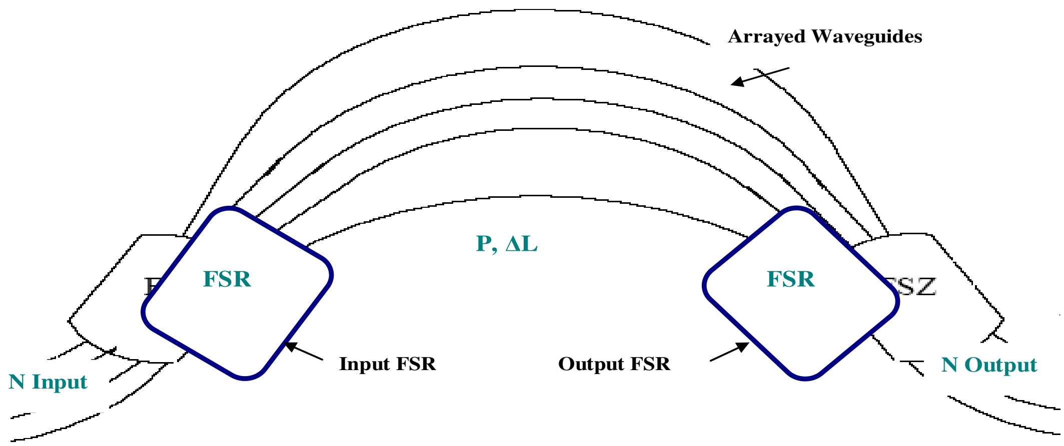


**Figure 1.** Schematic representation view of the N X N AWG.

tion ranges, FSR), connected by a dispersive waveguide array with the equal length difference between adjacent array waveguides. The operation principle of the AWG multiplexers/demultiplexers is described briefly as follows. Light propagating in the input waveguide is diffracted in the slab region and coupled into the arrayed waveguide by the first FSR. The arrayed waveguides has been designed such that the optical path length difference ΔL between adjacent array waveguides equals an integer (m) multiple of central wavelength $\lambda_0$ of the demultiplexer. As a consequence, the field distribution at the input aperture will be reproduced at the output aperture. Therefore, at this center wavelength, the light focuses in the center of the image plane (provided that the input waveguide is centered in the input plane). If the input wavelength is detuned from this central wavelength, phase changes occur in the array branches. Due to the constant path length difference between adjacent waveguides, this phase change increases linearly from the inner to outer array wave-guides, which causes the wave front to be tilted at the output aperture. Consequently, the focal point in the image plane is shifted away from the center. The positioning of the output waveguides in the image plane allows the spatial separation of the different wavelengths. The input consists of several channels, typically between 8 and 40 in commercial devices, carried on separate fre-quencies. Channel spacings of 100 or 50 GHz are common in commercial devices, although 25 GHz (Nippon Telegraph and Telephone Corporation, 2002) and 10GHz (Hiroaki et al., 1998) spacing have been achieved under laboratory conditions. The operational wavelength is commonly around 1.55 µm where attenuation is lowest in optical fibers. All waveguides in the AWG tend to be single-moded to ensure predictable propagation through the device.

## Basic design parameters of AWG model

After understanding the operation principle of AWG devices, depending on different materials, such as silica, or polymeric materials; and design requirements, such as diffraction, length difference of adjacent arrayed waveguides, focal length of the slab waveguide, free spectral range (FSR), maximum number of input/output wavelength channels, and maximum number of the arrayed waveguides. The basic design parameters are summarized in analytical equations as follows:

## Diffraction order

We expressed the corresponding grating order m to cover the C-band's spectral range from 1.528 to 1.56 µm. We can obtain the grating order m as a function of wavelength for a certain spectrum range as follows (Qiao et al., 2002):

$$Diffraction\ order\ (m) = \frac{\lambda_1}{\lambda_2 - \lambda_1}\ , \qquad (1)$$

So that the spectrum of the C band signal $\lambda_2$ operating at m order, do not overlap the spectrum of the optical signal $\lambda_1$, when operating at m+1 order, and the maximum allowable value for the optimization is approximately 155 at the center wavelength $\lambda_0$. The diffraction order m is an important parameter. Once the diffraction order m is determined, some other parameters of the AWG device are also determined, such as the length difference of adjacent waveguides, focal length of the slab waveguide, free spectral range (FSR), number of input/output wavelength channels, and number of the arrayed waveguides. In the following analysis, we investigate the relations between the diffraction order m and the above parameters, and carry on the parameter optimization.

## Length difference of adjacent arrayed waveguides

The path length difference between adjacent arrayed waveguides ΔL is given by the following expression (Spiekman and Amersfoort, 1996; Okamoto, 2000).

$$\Delta L = \frac{m\lambda_0}{n_c} \quad , \tag{2}$$

Where
m: is the diffraction order, $n_c$: is the effective refractive-index of AWG, and $\lambda_0$: is the center wavelength of the arrayed waveguide, μm.

## Focal length of the slab waveguide

The focal length of the slab waveguide is given by the following equation (Spiekman and Amersfoort, 1996; Okamoto, 2000);

$$L_f = \frac{n_s\, d^2\, n_c}{m\, \Delta\lambda\, n_g} \quad , \tag{3}$$

Where
$n_s$: is the effective index of the slab waveguide, d: is the pitch length of adjacent input/output channels and arrayed waveguides, μm, Δλ: is the wavelength channel spacing, nm, and $n_g$ : is the group refractive index and is given as the following:

$$n_g = n_c - \lambda_0 - \frac{dn_c}{d\lambda_0} \quad , \tag{4}$$

## Free spectral range (FSR)

An important property of the AWG is the free spectral range (FSR), also known as the demultiplexer periodicity. This periodicity is due to the fact that constructive interface at the output FSR can occur for a number of wavelengths. The free spectral range denotes the wavelength and frequency spacing between the maximum of the interface pattern because of the periodic characteristic of the AWG transfer function, and can be obtained as follows (Spiekman and Amersfoort, 1996; Okamoto, 2000):

$$FSR = \frac{\lambda_0\, n_c}{m\, n_g} \quad , \tag{5}$$

## Maximum number of the input/output wavelength channels

The maximum number of I/O wavelength channels $N_{max}$ depends on the FSR. The bandwidth of the multiplexed light, that is $N_{max}$ Δλ must be narrow than an FSR to prevent the overlapping of orders in the spectral region. Therefore, $N_{max}$ can be derived as (Spiekman and Amersfoort, 1996; Okamoto, 2000);

$$N_{\max} = \text{int}eger\left(\frac{FSR}{\lambda_0}\right) \quad , \tag{6}$$

## Number of the arrayed waveguides

The number of the arrayed waveguides P is not a dominant parameter in the AWG design because the wavelength channel spacing Δλ and maximum number of wavelength channels $N_{max}$ do not depend on it. Generally, P is selected so that the number of the arrayed waveguides is sufficient to make the numerical aperture (NA), in which they form a greater number than the input/output waveguides, such that almost all the light diffracted into the free space region is collected by the array aperture. As a general rule, this number should be bigger than four times the number of wavelength channels (Spiekman and Amersfoort, 1996; Okamoto, 2000);

$$P = 4N_{\max} = 4\,\text{int}eger\left(\frac{FSR}{\lambda_0}\right) \quad , \tag{7}$$

## RESULTS AND DISCUSSIONS

We assume that all the channels and arrayed waveguides have identical core sizes and have identical refractive-index profiles, and let the core width equal to core length a. We select the central wavelength $\lambda_0$ = 1.550918 μm (or 193.3 THz for frequency), which is one of the standard wavelength recommended by the international telecommunication union (ITU) (Kuznetsov et al., 2000) the wavelength spacing Δλ= 0.8 nm, the pitch length of adjacent input/output channels d = 15 μm, the refractive-index of the core $n_1$= 1.446, and that of silica cladding surrounding the core $n_2$= 1.442, so the relative refractive-index difference $\Delta n = \frac{n_1 - n_2}{n_1} = 0.28$ %.
Table 1 shows the typical values of the basic parameters for our AWG model for estimation the basic parameters design. Let us assume the effective refractive-index $n_c$ = 2.692, the refractive-index of the slab waveguide $n_{slab}$ = 3.06, and the group-index $n_g$ = 4.5 (Fukazawa et al., 2004).

The Figures from (2-7) assure the following results based on the assuming set of the parameters shown in Table (1).

As shown in Figure 2, as the optical signal wavelength $\lambda_1$ increases, the diffraction order m increases. There is a direct relation between optical signal wavelength $\lambda_1$ and diffraction order, as we fix $\lambda_2$ at the point 1.56 μm and increase $\lambda_1$, this increase the numerator and decrease the denumerator, this result in the diffraction order, m increases.

**Table 1.** Typical values of the basic design parameters in the proposed model.

| Parameter | Symbol | Value |
|---|---|---|
| Center wavelength | $\lambda_0$ | 1.550918 µm |
| Slab refractive-index | $n_s$ | 3.06 |
| Effective refractive-index | $n_c$ | 2.692 |
| Group refractive-index | $n_g$ | 4.5 |
| Wavelength spacing | $\Delta\lambda$ | 0.8 nm |
| Pitch length | d | 15 µm |
| Core refractive-index | $n_1$ | 1.446 |
| Cladding refractive-index | $n_2$ | 1.442 |
| Relative refractive-index difference | $\Delta n$ | 0.28% |

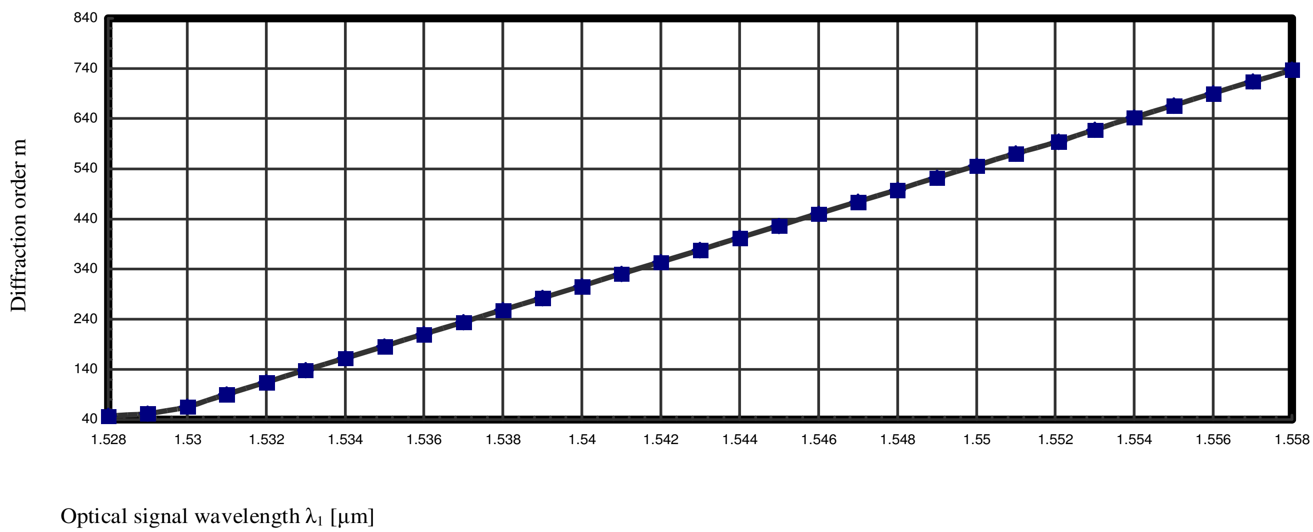


**Figure 2.** Variation of the diffraction order m against the optical signal wavelength at the assumed set of parameters.

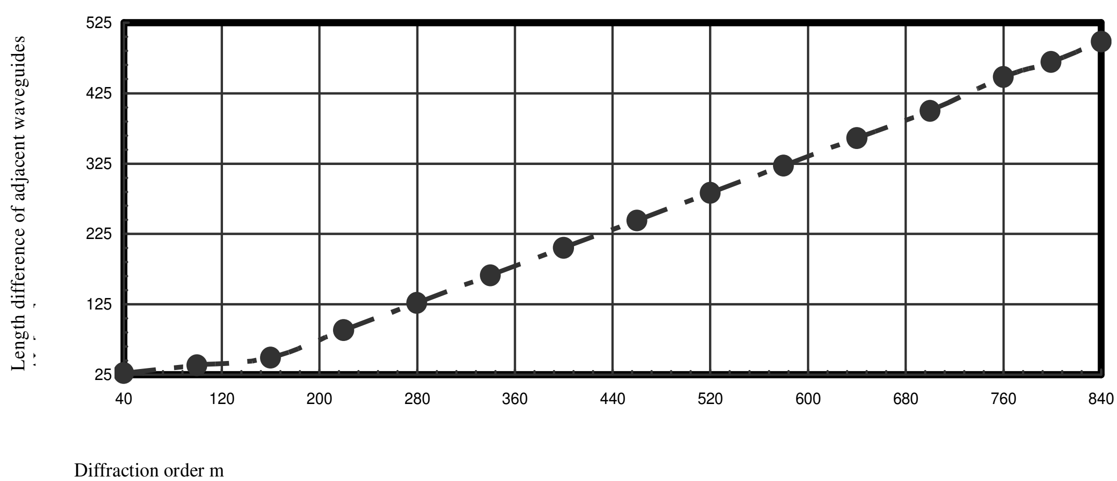


**Figure 3.** Variation of the length difference ΔL against the diffraction order at the assumed set of parameters.

As shown in Figure 3, as the diffraction order m increases, the difference of the adjacent arrayed waveguides ΔL also increases. There is a direct relation between m and ΔL, this leads to any increase in diffraction order m results in increasing in ΔL.

As shown in Figure 4, while the diffraction order m

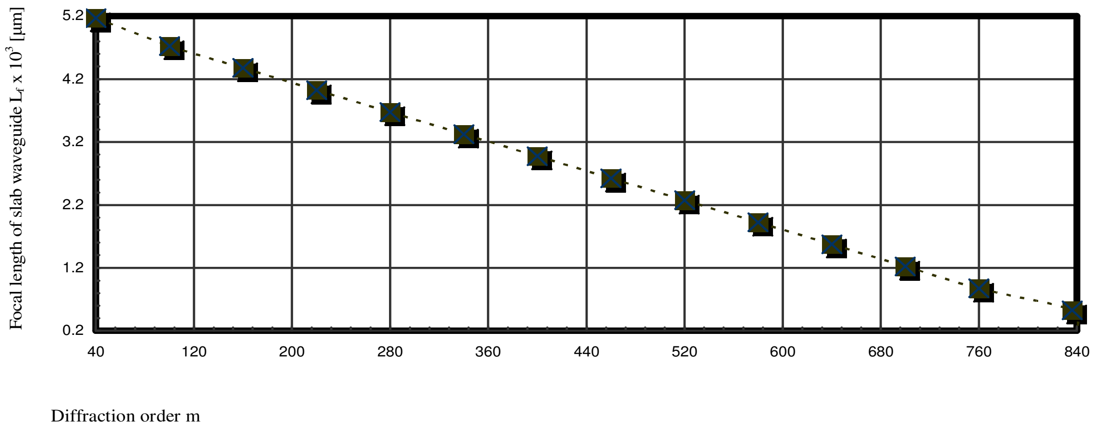


**Figure 4.** Variation of the focal length $L_f$ against the diffraction order at the assumed set of parameters.

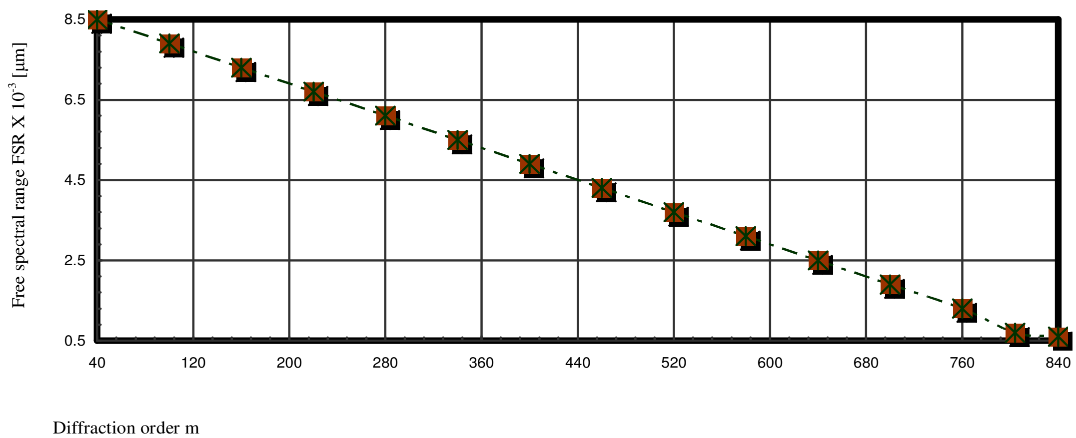


**Figure 5.** Variation of the FSR against the diffraction order at the assumed set of parameters.

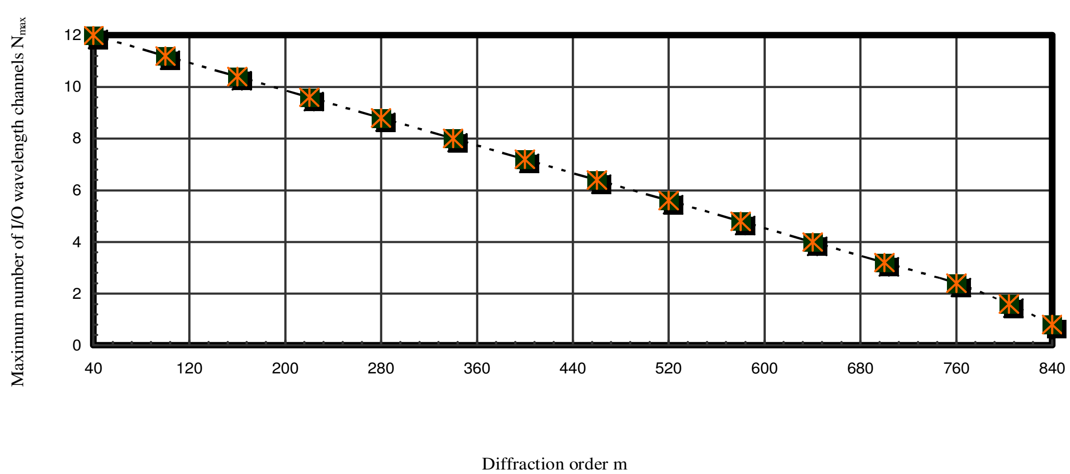


**Figure 6.** Variation of the number of I/O channels $N_{max}$ against the diffraction order at the assumed set of parameters.

increases, the focal length of the slab waveguide $L_f$ decreases.

As shown in Figure 5, while the diffraction order m increases, the free spectral range (FSR) decreases. As shown in Figure 6, while the diffraction order m increases, the maximum number of the input/output

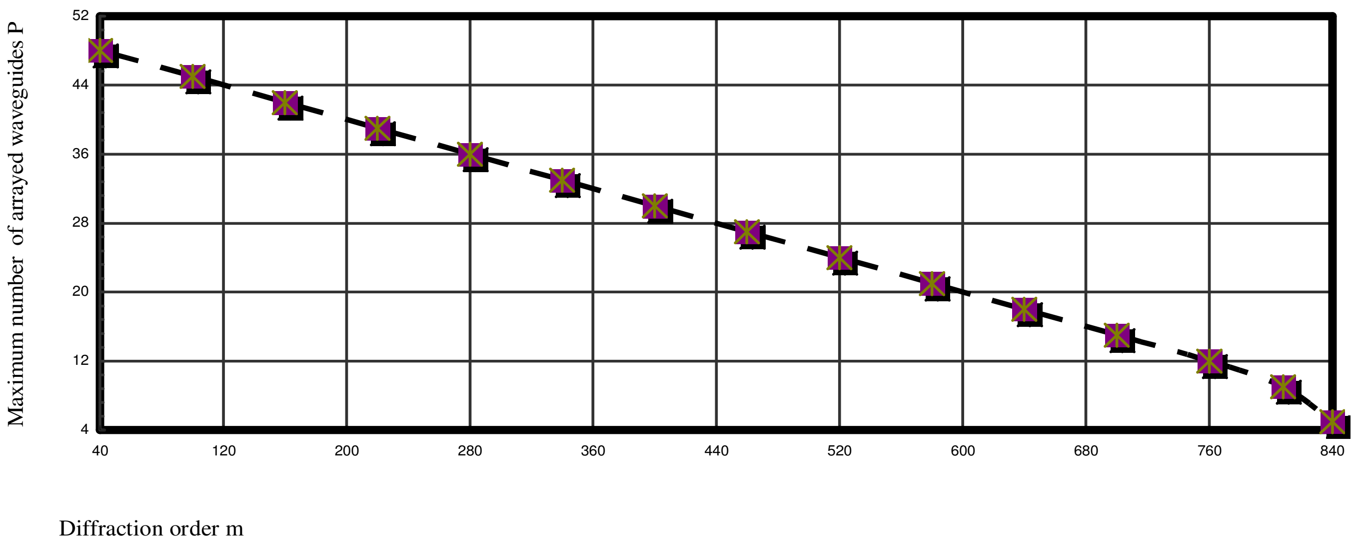


**Figure 7**. Variation of the number of arrayed waveguides P against the diffraction order at the assumed set of parameters.

**Table 2.** Estimated optimization parameters of AWG for C-band applications.

| Optimization parameters of AWG | value |
|---|---|
| Diffraction order, m | 155 |
| Length difference between adjacent waveguides, ΔL | 90 μm |
| Focal length of the slab waveguide, $L_f$ | 3322 μm |
| Free spectral range, FSR | 6 nm |
| Maximum number of Input/Output channels, $N_{max}$ | 8 |
| Number of arrayed waveguides, P | 32 |

wavelength channels decreases.

As shown in Figure 7, while the diffraction order m increases, the number of the arrayed waveguides decreases.

## Conclusion

In a summary, we have investigated theoretically the ba-basic design parameters of the silica-based AWG in the C-band spectral range (from 1.528 to 1.56 μm). It is found that the diffraction order m must be small in order to increase the maximum input/output wavelength channels and then to increase the number of the arrayed waveguides. Also, we have analyzed the optimization design parameters of the Arrayed Waveguide Grating (AWG) for the C-band applications as in Table 2.

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